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TESTS OF BONDED AND RIVETED SHEET-STRINGER PANELS

By Leonard Mordfin and I. E. Wilks

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SUMMARY

Tests were performed on 21 sheet-stringer panels of 75S-T6 aluminum alloy having alclad sheets nominally 0.051 inch thick and stringers nominally $3\frac{1}{2}$ inches apart. Nine panels had Z-stringers riveted to the sheets with 5/32-inch 17S-T3 aluminum-alloy universal-head rivets spaced at nominally $1\frac{1}{8}$-inch intervals. Nine panels had I-stringers bonded to the sheets with Araldite Type I adhesive. Three panels had I-stringers bonded to the sheets with Metlbond adhesive.

Three panels of each type, having five stringers each and over-all dimensions of approximately 18 by 15 inches, were tested in axial flat-end compression. Three riveted panels and three Araldite bonded panels having five stringers each with the center stringer protruding beyond the sheet on one end and having over-all dimensions of approximately 18 by 15 inches were tested with load applied axially to the protruding end of the center stringer. Three riveted panels and three Araldite bonded panels having two stringers each and over-all dimensions of approximately $12\frac{1}{2}$ by $4\frac{1}{2}$ inches were tested in bending with a load applied at the center of an 8-inch span between simple supports. All tests were carried to failure and strain and deformation measurements were made.

The test results did not indicate any great superiority of one type of construction over the other but rather that the choice in any given case would depend upon the particular designs being compared. The principal advantages of the bonded construction appeared to result from the broad area of attachment possible between sheet and stringers. The principal disadvantage seemed to be the mode of failure in flat-end compression.

The tests also showed that the scatter of results obtainable with bonded construction was not significantly greater than that obtainable with riveted construction and that cleavage was not always the governing factor in the strength of bonded panels.

INTRODUCTION

Because of the relative ease and economy with which large structural joints may be bonded, considerable interest has centered upon the possibility of substituting adhesives for rivets in the fabrication of certain aircraft structural components. One such component, the flat sheet-stringer panel, is exceptionally well suited geometrically to bonding. The design and selection of such panels, however, are presently in a dubious state because of the relatively small amount of published data on the relative merits of bonding and of riveting in sheet-stringer construction (refs. 1 and 2).

The purpose of the investigation reported herein was to obtain additional data of this kind from tests performed on bonded and on riveted sheet-stringer panels, and to interpret those data, where possible, in terms of comparative strength, stability, and load-distribution properties.

This investigation was conducted at the National Bureau of Standards under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

SPECIMENS

Design of Specimens

It would appear that the most straightforward manner of evaluating the relative merits of bonding and of riveting in sheet-stringer construction would be to test specimens which were alike in every respect except in the method of attachment of the stringers to the sheet. However, the behaviors of riveted and bonded joints under load are sufficiently different that in order to gain the full advantages of a bonded panel it is not enough merely to substitute an adhesive for rivets in a conventionally designed panel. To use identical stringers for both the bonded and the riveted panels would be to impose a structural penalty upon one or the other.

It was therefore specified that the alternate fabrications should each employ the best practice to produce a panel for the same service. The contract for manufacture of the panels was awarded to the Consolidated Vultee Aircraft Corp. since it was experienced in making both riveted and bonded panels. It was agreed that the two sets of panels should have lengths, widths, and slenderness ratios that were about equal. The limited availability of materials and shapes made it impossible for the manufacturer to achieve this entirely. It was decided to proceed with the best materials and shapes at hand to avoid the lengthy delay which would otherwise have been necessary.

The riveted panels were fabricated with Z-stringers, which require only one row of rivets per stringer and which are used widely in the aircraft industry because they allow free access for riveting tools. The mechanical properties of Z-stiffened panels have been investigated extensively by the NACA.

For the bonded panels an I-stringer was designed to have a suitable gluing area and to conform to the known properties of bonded joints. In general, bonded joints are about equally strong in shear and tension. (ref. 3). The peeling, or cleavage, strength of bonded joints is relatively low, however, and the loading of bonded joints in peeling or cleavage should be avoided (ref. 4). Therefore, the I-stringers used on the bonded panels were designed to minimize the tendency of the bond to peel because of buckling of the sheet under load. This design was based on the results of tests reported in reference 5 which show that an outstanding flange of high stiffness resists twisting of the stringer and the accompanying buckling of the sheet and an attached flange of low stiffness (see notch at edges, fig. 1) reduces the peeling forces produced in the joint by buckling of the sheet under load.

Dimensions and Components

In order to simplify the designation and discussion of the panels tested, each panel was assigned two letters of the alphabet as well as a number. The first letter specifies the medium used to fasten the stringers to the sheets; that is, R stands for rivets, A, Araldite Type I adhesive, and M, Metlbond adhesive. The second letter indicates the type of test to which the specimen was subjected; that is, f stands for flat-end compression, p, protruding-stringer compression, and b, bending. (These three types of tests (fig. 2) will be described in subsequent sections of this report.) Thus, for example, panel Af-3 had stringers fastened to the sheet with Araldite Type I adhesive and was tested in flat-end compression.

The average dimensions of the stringers and the panels are given in figures 1, 3, and 4 and in table 1. Panels Ap-7, Ap-8, Ap-9, Rp-10, Rp-11, and Rp-12 were fabricated with their center stringers protruding beyond one end of the sheet. The center-to-center distance between stringers was nominally $3\frac{1}{2}$ inches on all panels.

The panels were all 75S-T6 aluminum alloy, the sheets being alclad and the stringers bare. The Z-stringers of the riveted panels were extruded from Die K32733 and were fastened to the sheets with universal-head 5/32-inch 17S-T3 aluminum-alloy rivets. The rivets were spaced at about $1\frac{1}{8}$-inch intervals, except for the two end rivets on each stringer which were each 1/2 inch from the adjacent rivet. The I-stringers of the bonded panels were extruded from Die K13669 and modified by machining and bonding operations to meet the design requirements mentioned previously.

The original set of panels obtained was comprised only of panels Af-1 to Rb-18 (table 1). Relatively low strengths were subsequently exhibited by the Araldite bonded panels in flat-end compression tests. The Consolidated-Vultee Aircraft Corp. indicated that panels using Metlbond adhesive might give greater strength. They therefore fabricated three additional panels, Mf-19, Mf-20, and Mf-21, with this adhesive for use in this investigation.

TESTS AND RESULTS

Flat-End Compression

Araldite bonded panels Af-1, Af-2, and Af-3, Metlbond bonded panels Mf-19, Mf-20, and Mf-21, and riveted panels Rf-4, Rf-5, and Rf-6 were tested in axial flat-end compression (fig. 2(a)). The Araldite bonded panels and the riveted panels were tested to failure in a 120,000-pound-capacity Baldwin-Southwark Tate-Emery hydraulic testing machine. Panel Mf-19 was also tested in this machine but did not fail when the capacity of the machine was reached. After removal of the load, an average permanent set of less than 0.02 percent remained. This panel and panels Mf-20 and Mf-21 were then tested to failure in a 400,000-pound-capacity Tinius Olsen hydraulic testing machine. The test setup for all of these panels was essentially the same and is shown in figures 5 and 6.

The ends of the panels were ground flat and parallel while held in a jig which kept the sheets flat. A similar type of jig was clamped upon the panels before insertion between the bearing plates in the testing machine to retain the parallelism of the ends. Plaster of Paris (A, fig. 5) about 1/16 inch thick was cast between the bearing plates and the heads of the machine to take up any nonparallelism between them. The unloaded edges of the panels were free. At a load of about 750 pounds the jig was removed. At 10 percent of the maximum load the strain distribution across the width of the panels was uniform within 10 percent in most cases and within 14 percent in the worst case, panel Af-1.

Axial shortening of the panels was measured with two 1-inch dial gages (B, fig. 5) having a least count of 0.001 inch. These dial gages were fixed to the upper bearing plate, one near each vertical edge of the panel being tested. Vertical extension rods (C, fig. 5) were mounted between the dial gages and dimpled points in either the lower bearing plate or the lower head of the machine.

Axial strain in the panels was measured with SR-4 wire strain gages. Six gages were cemented to the individual panels near each loaded edge, three on stringers and three on the sheet. These were used to observe the load distribution across the width of the panel. An erratic load distribution was observed on panel Rf-5 at about 35,000 pounds, so the load was removed. The plaster of Paris caps were recast and the new strain distribution was satisfactory. Permanent set due to the initial loading was measured and found to be negligible.

Wire strain gages were also placed at various locations at the mid-length of the center stringer and the sheet.

Figure 7 is a plot of average axial stress versus average axial strain for Araldite bonded panel Af-2, riveted panel Rf-4, and Metlbond bonded panel Mf-20. These curves are representative of all of the nine panels tested in flat-end compression. Average axial stress was taken as total load divided by total cross-sectional area, and average axial strain was computed from the readings of the dial gages and the measured lengths of the panels. The slopes of the curves are substantially the same for all three panels and exhibit an average effective modulus of about 9×10^6 psi. The low value of the modulus determined in this way is believed due to the fact that the dial gages, being mounted on the bearing plate, indicated greater shortening than actually occurred in the panel.

The distribution of the panel load between stringers and sheet was computed from strain-gage readings at the midlength of the center stringer. It was assumed that the strain in each stringer varied linearly with distance from the sheet. This was shown in reference 6 to hold until stringer instability occurred. It was further assumed that the total stringer load equaled five times the center stringer load. This is reasonably justified by the fact that the strain distribution across the five stringers was uniform within 15 percent up to failure. The load carried by the center stringer was computed from the strain at its centroid, a modulus of elasticity of 10.3×10^6 psi, and its cross-sectional area.

Stringer loads as functions of total load are given in figure 8 for Araldite bonded panels Af-2 and Af-3, in figure 9 for riveted panels Rf-4 and Rf-6, and in figure 10 for Metlbond bonded panels Mf-19, Mf-20, and Mf-21. The difference in abscissas between stringer load and the plotted total load line gives the sheet load. Insufficient strain gages were employed on panels Af-1 and Rf-5 to compute the load distribution.

It can be seen that the load in the panels was in agreement with the assumption of a uniform stress distribution before buckling of the sheet between stringers occurred. Table 2 gives the computed sheet and stringer loads and the computed average stresses in these members for the total panel loads at which sheet buckling was first observed. The sheets of the riveted panels buckled at a 40 percent lower average sheet stress than the sheets of the bonded panels. This is undoubtedly due to the broader area of contact between sheet and stringers in the bonded panels and the resulting lesser width of unsupported sheet. Above the sheet buckling load, figures 8, 9, and 10 indicate that the effective width of sheet is greater for the bonded panels than for the riveted, probably for the same reason. The buckling of the sheet in the riveted panels included inter-rivet buckling and was more severe than in the bonded panels. Figure 6 shows the general type of buckling observed. The addition of a second row of rivets on the riveted panels, such as is required with hat-section stringers, would reduce the unsupported width of sheet between rivet lines and could conceivably increase the sheet buckling stress even above that obtained with the bonded panels. This, however, entails an additional manufacturing operation and does not eliminate inter-rivet buckling. The use of a smaller rivet pitch, however, would tend to raise the load required for inter-rivet buckling.

Failure in the Araldite bonded panels Af-1, Af-2, and Af-3 occurred in the bond. In panels Af-1 and Af-2 this failure took place at a load of about 100,000 pounds with the sheet explosively ripping free of the stringers and blowing out of the testing machine. The stringers remained in the testing machine in perfect testing position (fig. 11) and were then tested to failure. This failure was due to column action. The stringers buckled in a plane parallel to the original plane of the sheet and some of the reinforcing strips ripped off (fig. 12).

The bond of panel Af-3 failed at a considerably lower load (78,000 pounds) than those of panels Af-1 and Af-2. At this point two-thirds of the sheet ripped free (fig. 13). Further testing produced a maximum load of 105,200 pounds at which point the entire sheet ripped free and the stringers buckled. Examination of the bonded surfaces after failure indicated that the premature bond failure in panel Af-3 was due to inferior fabrication. The adhesive on the bonded surfaces of panels Af-1 and Af-2 was more or less uniform and porous, while on panel Af-3 some areas had no adhesive while others showed excess adhesive and no porosity. The inferior fabrication of panel Af-3 was not evident before testing.

The maximum loads and average ultimate stresses for panels Af-1, Af-2, and Af-3 are given in table 3.

Riveted panels Rf-4, Rf-5, and Rf-6 all failed because of local buckling of sheet and stringers between rivets near the midlength of the panels (fig. 14). Failure occurred at maximum load in all three cases. The loads and average stresses at failure are given in table 3.

Failure of the Metlbond bonded panels Mf-19, Mf-20, and Mf-21 was due to column buckling of the stringers in a plane parallel to the plane of the sheet (fig. 15) and the consequent destruction of most, but not all, of the bond. Failure occurred at maximum load. The maximum loads and average ultimate stresses are given in table 3.

Table 3 shows that the average stress at maximum load is about 30 percent greater for the Metlbond bonded panels than for the riveted panels. The average stress at maximum load for the riveted panels would, of course, be higher if it had been fabricated with stringers having the same sectional properties as the stringers of the bonded panels, since after sheet buckling the stringers carry most of the stress. The strength of riveted panels also depends on the choice of rivet diameter and pitch (see ref. 7).

The greater strength of the Metlbond bonded panels as compared with that of the Araldite bonded panels indicates that the use of a stronger adhesive and/or a superior bonding technique will also strengthen bonded panels.

The mode of failure of the Metlbond bonded panels shows that, for panels of the type tested, cleavage is not always the primary factor in determining strength.

Protruding-Stringer Compression

Araldite bonded panels Ap-7, Ap-8, and Ap-9 and riveted panels Rp-10, Rp-11, and Rp-12 were each tested in axial compression with the load applied through the protruding center stringer (fig. 2(b)). The ends of the protruding stringers and the opposite ends of the individual panels were ground flat and parallel. The same general test setup was used as in the flat-end compression tests except that a smaller bearing plate was used over the protruding stringer. The test setup is shown in figures 16 and 17. The tests were run in a 120,000-pound-capacity Baldwin-Southwark Tate-Emery hydraulic testing machine.

The panels assumed distorted shapes at low loads, and this distortion increased in intensity up to failure. The lower ends of the four stringers which were not directly loaded lifted off of the lower bearing plate although the bottom of the sheet remained in contact throughout the test (figs. 16 and 17). The strains in the four indirectly loaded stringers and the strains in the sheet near its unloaded edges were relatively small. The upper end of the panel took on a bowed shape (fig. 17) although the lower end remained straight. No buckling of the sheet between stringers was observed.

Figures 18 and 19 give the load carried by the center stringer as a function of its length for total applied loads of approximately 1/4, 1/2, and 3/4 of initial failure load. Curves have been faired through the points corresponding to strain-gage locations on the stringer. The stringer load at each station was computed by the method outlined previously with one exception. The strain at the centroid of the center stringer at the lowest station was taken as equal to the strain on its outstanding flange at that level. This is tantamount to assuming that the bending strain at that level was negligible. The basis for this assumption was that the total eccentricity of loading was only about 0.3 inch. Furthermore, this station was less than 2 inches above the bottom of the stringer where there was no bending whatever because of the manner of loading. At best, however, the stringer loads shown in figures 18 and 19 at the lowest stations are only approximations.

Figures 18 and 19 show that at all loads all the center stringers transferred approximately equal percentages of the applied load to the remainder of their respective panels. Over the first half of the length the Araldite bonded center stringers transferred about 55 percent of the applied load. For the riveted center stringers this value was 59 percent. This indicates that prior to failure the ability to transfer axial compressive load through shear was just slightly greater for the riveted construction than for the bonded construction. This is more or less as expected, since the riveted stringers accounted for a slightly smaller percentage of the cross-sectional area of the riveted panels than the bonded stringers did for the bonded panels.

Bonded panel Ap-8 and riveted panel Rp-12 were tested first. They had protrusions of nominally 1/2 inch. At 19,000 pounds the top half of the bond holding the center stringer to the sheet of panel Ap-8 ripped. Further testing produced a maximum load of 25,200 pounds where the bond failed almost completely and the stringer buckled in a plane parallel to the sheet because of column action. Riveted panel Rp-12, however, failed at 14,100 pounds because of local crushing of the protruding portion of the center stringer. Since the latter type of failure did not offer a good comparison between the two types of joints, the protrusions of the remaining panels Ap-7, Ap-9, Rp-10, and Rp-11 were cut down to 0.1 inch in an attempt to eliminate local failures in the protrusions. Bonded panels Ap-7 and Ap-9 then failed similarly to panel Ap-8 (fig. 20). Riveted panel Rp-11 also failed satisfactorily. At 12,500 pounds the top rivet sheared. Further testing yielded a maximum load of 13,400 pounds where the top half of the center stringer buckled torsionally (fig. 21(a)). Inspection showed the top nine rivets to be sheared. Riveted panel Rp-10, unfortunately, failed like panel Rp-12 because of local crushing in the protrusion (fig. 21(b)).

The initial failure loads, the maximum loads, and the strength-weight ratios at each of these two loads are given in table 4. Since figures 18 and 19 show that for a given applied load both joints carry equal shear loads, table 4 indicates that the shear strength, in pounds, of the Araldite bonded joint is greater than that of the riveted joint. Table 4 shows, further, that the strength-weight ratios for the riveted and the Araldite bonded panels at initial failure are nearly equal. At maximum load, the strength-weight ratio of the Araldite bonded panels is roughly 20 percent higher than that of the riveted panels.

It is interesting to note, at this point, that the shear strength of the bonded joints cannot be computed from nominal ultimate-shear-strength values such as those given in references 3 and 5, which are obtained from tests on joints having short laps. This is because the strength of a bonded joint is not proportional to its area, but rather, as stated in reference 4, there is an optimum depth of lap beyond which shear strength is not appreciably increased.

Bending

Bending tests (fig. 2(c)) were performed on Araldite bonded panels Ab-13, Ab-14, and Ab-15 and on riveted panels Rb-16, Rb-17, and Rb-18. The test setup is shown in figures 22 and 23. The panels were simply supported over an 8-inch span, the supports being approximately 2 inches from the ends of the panel. A single concentrated load was applied at the center of the span, with the panels mounted so that the sheets were compressed. The simple support was achieved by setting the panels upon knife edges A which were free to move upon rollers B (fig. 23). The tests were performed in a 120,000-pound-capacity Baldwin-Southwark Tate-Emery hydraulic testing machine, and the load was applied through a knife edge acting upon a set of loading plates C (fig. 23) which rested upon the individual panels. The purpose of the loading plates was to eliminate large local stresses at the point of application of the load. For the riveted panels, the lowest of these loading plates had holes drilled in it to provide clearance and room for movement of the protruding rivet heads. Plaster of Paris was cast above the loading knife edge to assure parallelism of this knife edge and the individual panels.

At low loads the Z-stringers of the riveted panels assumed slightly distorted shapes. The webs and outstanding flanges of these stringers bowed in a direction parallel to the plane of the sheet, the free edges of the outstanding flanges lifted off the supports, and the sheets twisted somewhat. The latter two observations may be seen in figure 23. These distortions increased in magnitude with applied load.

Very little sheet buckling was observed with either type of panel, and when observed it was only at the center of the sheets at loads approaching failure.

Deflection of the panels was measured with 0.001-inch dial gages. Three gages were located on each side of the panel as shown in figure 22. One dial gage was mounted under the center of each of the two stringers, and dial gages were mounted at each end of the two supports to measure the vertical displacement of the supports under load. It was found that the supports deflected less than 8 percent as much as the center of the panel did. The net center deflection of the panel was taken as the average of the center displacements of the two stringers minus the average of the four support deflections.

Load-deflection curves for the six panels tested in bending are given in figure 24. Simple beam theory states that

$$d = \frac{PL^3}{48EI}$$

where d is the deflection, P is the load, L is the span of the beam, E is the modulus of elasticity, and I is the moment of inertia. For the panels tested in bending, this relation gives the ratio $P/dI = 48E/L^3 = 960$ kips/(inch)^5 below the proportional limit. Taking slopes from figure 24 and moments of inertia from table 1, it is found that for the bonded panels this ratio is actually 480 kips/(inch)^5 and for the riveted panels 370 kips/(inch)^5. Obviously, neither type of panel is structurally efficient in bending over such a short span although the bonded panels are about 30 percent more so than the riveted panels. The low observed flexural rigidities of the panels were probably due in part to shear lag in the sheets and in part to shear deflections of the stringer webs. The greater width of unsupported sheet in the riveted panels probably caused a greater amount of shear lag than in the bonded panels. The observed distortions of the Z-stringers may also have caused a reduction of the stiffness of the riveted panels. Slip in the riveted joints and deformation in the bonded joints probably increased the deflections due to shear.

Strain was measured at several locations on the individual panels with SR-4 wire strain gages. In figures 25 and 26 are given several load-strain curves for a representative Araldite bonded panel and a representative riveted panel, respectively. The maximum bending strain, located at the center of the outstanding flanges of the stringers, is seen to be linear with load up to yielding, after which it increases greatly with little increase in load. The strain of the sheets is also seen to be linear with load up until high loads, after which it shows a decrease with increased load. This decrease is probably attributable to either (1) yielding in the joints due to shear and the consequent reduction of the amount of flexure stress transmitted to the sheets or (2) movement of the neutral planes of the panels toward the sheets due to the yielding of the outstanding flanges of the stringers. It is not definitely apparent which, if either, of these possibilities was the actual cause.

Strain gages 10 and 11, figures 25 and 26, measured the vertical strains on the webs of the stringers directly below the applied load. These strains are seen to be linear with load up to high loads where they showed slight departures from linearity. These departures from linearity are attributed to the observed bending of the webs.

Failure of all panels was due to buckling of both stringer webs directly under the applied load, despite the fact that the outstanding stringer flanges had been stressed far beyond the elastic limit. With panels Ab-13, Ab-15, Rb-16, and Rb-18, this buckling increased at essentially constant load until fracture of the webs occurred. Representative failures are shown in figure 27. With panels Ab-14 and Rb-17 no fractures were obtained because the test setup collapsed from excessive movement of the supports caused by the sudden buckling of the webs and the accompanying deflection and shortening of the panels. Hence, while no fracture was obtained in these two tests, the maximum loads recorded are undoubtedly very close to the actual maximum loads and may be safely considered as such. In the test of panel Rb-16, two rivets failed in shear during the few seconds that elapsed between the start of buckling and the fracture of the webs.

The maximum loads of all six panels are given in table 5. Since the fractures occurred in the stringers rather than in the joints, these values do nct present a means of comparing the strengths of the two types of joints in shear due to bending. One conclusion that may be drawn, however, is that both the riveted and the bonded joints are sufficiently strong in shear due to bending, since failure occurred elsewhere in the panels. The importance of this conclusion becomes apparent when it is recognized that sheet-stringer construction is not generally subjected to flexure so severe as that which was applied in these tests.

DISCUSSION

The results obtained in the tests performed do not indicate any universal superiority of one type of construction over the other. Rather, they show that the properties of both types are of the same general order of magnitude. In a comparison between two specific panels, one bonded and the other riveted, a detailed examination of the geometry of the two as well as of the riveting and bonding involved would be necessary before a choice on the basis of mechanical properties could be made.

The primary advantage of bonded sheet-stringer panels over conventional ones using one line of rivets per stringer lies in the increased sheet stability that is obtained by bonding. A symmetrical stringer can be employed, and the broad area of attachment between sheet and stringers reduces the unsupported width of sheet, thus raising the load necessary to produce buckling of the sheet between stringers. After this buckling does occur, the broad area of attachment between sheet and stringers provides a greater effective width of sheet. In addition, inter-rivet buckling is eliminated and stress concentrations near the rivet heads for buckling between stringers are also eliminated. Some evidence was obtained in the protruding stringer tests that the bonded joints had greater shear strength than the riveted joints, but this condition would undoubtedly vary with the dimensions and the techniques of fabrication of any particular bonded and riveted joints being compared.

A matter of primary concern in the aircraft industry is with regard to possible scatter of strength obtainable with bonded construction. With the exception of panel Af-3, which was found after testing to have been poorly fabricated, the scatter of data for each of the two types of bonded panels was about the same as that obtained for the riveted panels.

Two specific results obtained from the tests on bonded panels seem worth stressing. First, the tests of the Metlbond bonded panels indicated that with proper design and fabrication cleavage may not be the primary factor governing the strength of sheet-stringer panels. Second, the tests of the bonded bend specimens showed that the bonded joints, like the riveted ones, were strong enough to have suffered almost no visible damage under high bending loads which eventually caused fracture of the webs of the stringers.

The primary disadvantage of bonded sheet-stringer panels seems to be in the mode of failure in flat-end compression. When maximum load was reached, the bonded panels experienced almost complete destruction with no warning signs other than a few preliminary cracking noises. The failure of the riveted panels, on the other hand, was confined to local buckling of sheet and stringers between rivets near the mid-length of the panels.

CONCLUDING REMARKS

Static tests were performed on riveted and bonded sheet-stringer panels at room temperature. The results of these tests indicate that the static strength properties of both types of construction are comparable. The stability of the sheet is greater for the bonded panels. The ability to spread a concentrated load is about the same for both the riveted and the bonded panels. The tendency toward widespread separation of sheet and stringers at failure of the bonded panels would make them less desirable in certain applications. The premature failure of one bonded panel due to faulty bonding indicates a need for special precautions in the fabrication technique when such failures cannot be tolerated.

National Bureau of Standards,
Washington, D. C., April 21, 1953.

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TABLE 1.- DIMENSIONS OF PANELS

Panel	Type (a)	Number of stringers	Length, in.	Width, in.	Sheet thickness, in.	Weight, lb	Length of protrusion, in.	Cross Section		
								Area of each stringer, sq in.	Area of panel, sq in.	Moment of inertia of panel, $in.^4$
Af-1	x	5	17.93	15.33	0.0510	5.06	0	0.40	2.80	1.33
Af-2	x	5	17.85	15.35	.0510	5.04	0	.40	2.80	1.33
Af-3	x	5	17.98	15.33	.0505	5.10	0	.40	2.80	1.33
Rf-4	y	5	17.99	15.05	.0508	3.52	0	.23	1.90	.71
Rf-5	y	5	18.00	15.04	.0505	3.52	0	.23	1.90	.71
Rf-6	y	5	17.97	15.03	.0506	3.52	0	.23	1.90	.71
Ap-7	x	5	[b]17.96	15.28	.0511	5.18	.10	.40	2.80	1.33
Ap-8	x	5	[b]17.96	15.30	.0504	5.10	.47	.40	2.80	1.33
Ap-9	x	5	[b]17.96	15.35	.0505	5.12	.10	.40	2.80	1.33
Rp-10	y	5	[b]18.00	15.05	.0506	3.54	.10	.23	1.90	.71
Rp-11	y	5	[b]18.01	15.06	.0506	3.53	.10	.23	1.90	.71
Rp-12	y	5	[b]17.89	15.02	.0504	3.50	.48	.23	1.90	.71
Ab-13	x	2	12.42	4.76	.0498	1.31	0	.40	1.05	.50
Ab-14	x	2	12.40	4.77	.0504	1.30	0	.40	1.05	.50
Ab-15	x	2	12.38	4.76	.0514	1.31	0	.40	1.05	.50
Rb-16	y	2	12.39	4.38	.0504	.86	0	.23	.68	.26
Rb-17	y	2	12.37	4.38	.0504	.90	0	.23	.68	.26
Rb-18	y	2	12.39	4.39	.0503	.90	0	.23	.68	.26
Mf-19	z	5	18.18	16.02	.0511	4.93	0	.35	2.56	1.13
Mf-20	z	5	17.91	16.02	.0504	4.84	0	.35	2.56	1.13
Mf-21	z	5	18.17	16.02	.0511	4.93	0	.35	2.56	1.13

[a] x, stringer shown in figure 1; fastened with Araldite
y, stringer shown in figure 3; fastened with rivets
z, stringer shown in figure 4; fastened with Metlbond.

[b] Not including protrusions.

TABLE 2.- BUCKLING OF SHEET BETWEEN STRINGERS

IN FLAT-END COMPRESSION TESTS

Panel	Observed total load		Computed stringer load		Computed sheet load	
	lb	psi	lb	psi	lb	psi
Af-1	73,000	26,100	(a)	(a)	(a)	(a)
Af-2	68,000	24,300	51,400	25,400	16,600	21,300
Af-3	67,000	23,900	49,900	24,700	17,100	21,900
Average (Araldite bonded)		24,800		25,000		21,600
Rf-4	23,000	12,100	13,800	12,200	9,200	11,900
Rf-5	18,000	9,470	(a)	(a)	(a)	(a)
Rf-6	27,000	14,200	16,300	14,400	10,700	13,900
Average (riveted)		11,900		13,300		12,900
Mf-19	56,000	21,900	36,700	21,100	19,300	23,600
Mf-20	58,000	22,700	39,800	22,900	18,200	22,200
Mf-21	59,000	23,100	40,900	23,500	18,100	22,100
Average (Metlbond bonded)		22,600		22,500		22,600

[a]Not computed because of insufficient strain gages on panels.

TABLE 3.- FAILURE OF FLAT-END COMPRESSION PANELS

Panel	Maximum load, lb	Average ultimate stress, psi
Af-1	104,600	37,400
Af-2	101,800	36,400
Af-3	[a]105,200	[a]37,600
Average (Araldite bonded)	103,900	37,100
Rf-4	82,700	43,500
Rf-5	84,700	44,600
Rf-6	84,100	44,200
Average (riveted)	83,800	41,000
Mf-19	140,000	54,800
Mf-20	134,000	52,400
Mf-21	142,000	55,600
Average (Metlbond bonded)	139,000	54,300

[a]Initial failure was at 78,000 lb or 27,900 psi.

TABLE 4.- FAILURE OF PROTRUDING-STRINGER PANELS

Panel	Initial failure[a]		Maximum load	
	Load, lb	Strength/ weight, kips/lb	Load, lb	Strength/ weight, kips/lb
Ap-7	16,000	3.09	23,500	4.54
Ap-8	19,000	3.73	25,200	4.94
Ap-9	19,100	3.73	26,400	5.16
Average (bonded)	18,000	3.52	25,000	4.88
Rp-10	None	None	[b]15,700	4.44
Rp-11	12,500	3.54	13,400	3.80
Rp-12	None	None	[b]14,100	4.03
Average (riveted)	12,500	3.54	14,400	4.09

[a]Shearing of joint.

[b]Local failure in protrusion.

TABLE 5.- FAILURE OF PANELS IN BENDING TESTS

Panel	Maximum load, lb
Ab-13	24,000
Ab-14	27,900
Ab-15	26,200
Average (bonded)	26,000
Rb-16	13,400
Rb-17	13,700
Rb-18	14,300
Average (riveted)	13,800

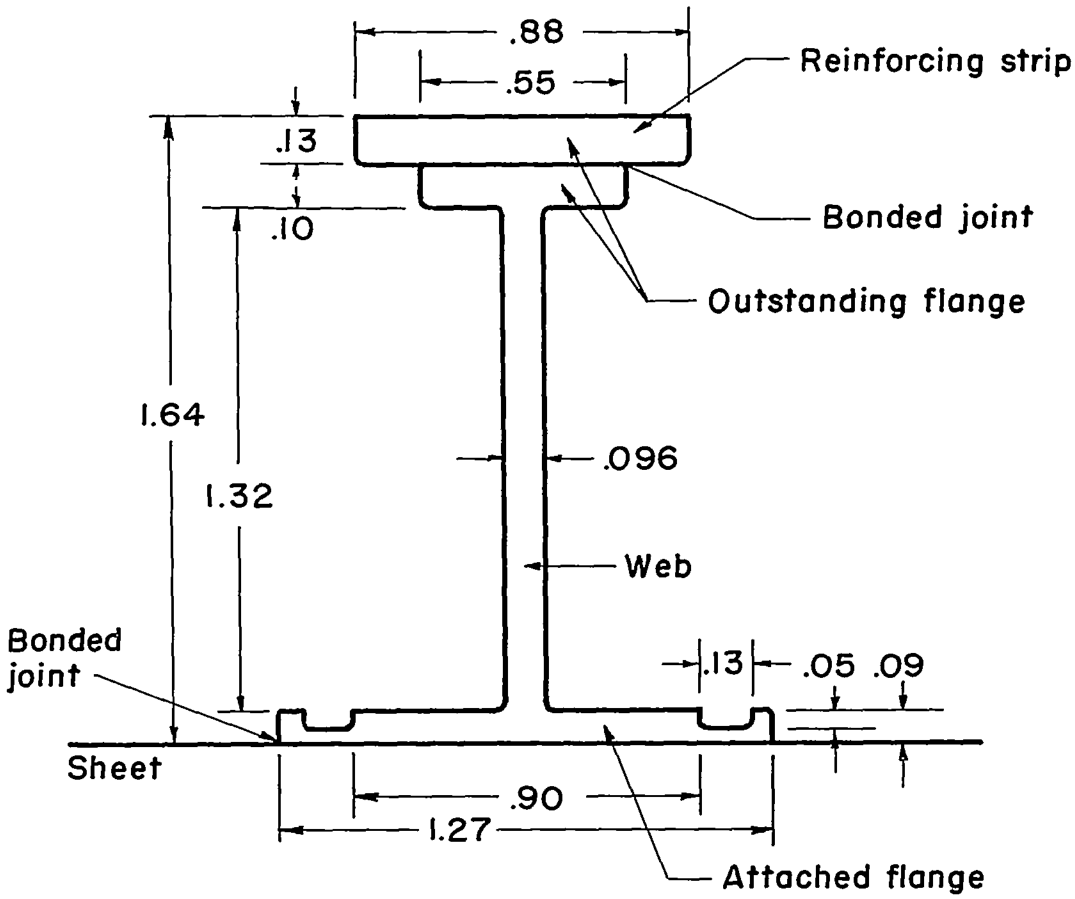
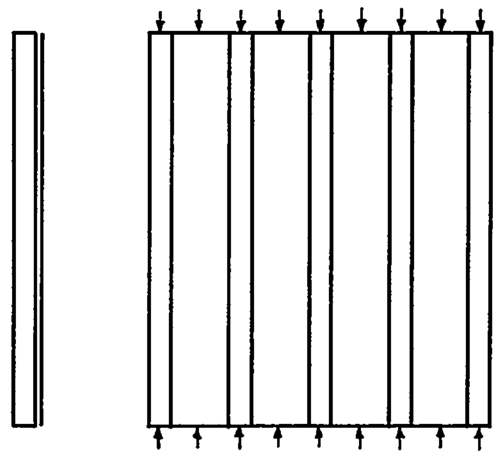
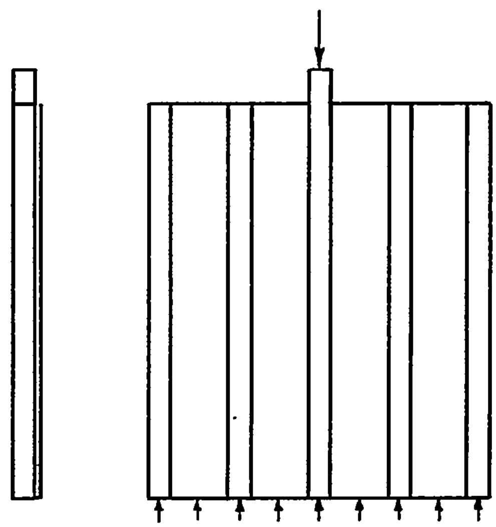


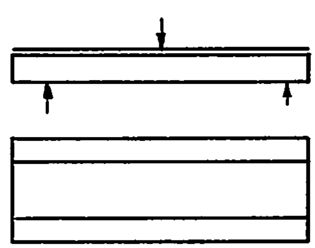
Figure 1.- Average cross-sectional dimensions of stringers of Araldite bonded panels Af-1, Af-2, Af-3, Ap-7, Ap-8, Ap-9, Ab-13, Ab-14, and Ab-15. All dimensions are in inches.



(a) Axial flat-end compression.



(b) Axial protruding-stringer compression.



(c) Bending.

Figure 2.- Schematic representation of tests performed.

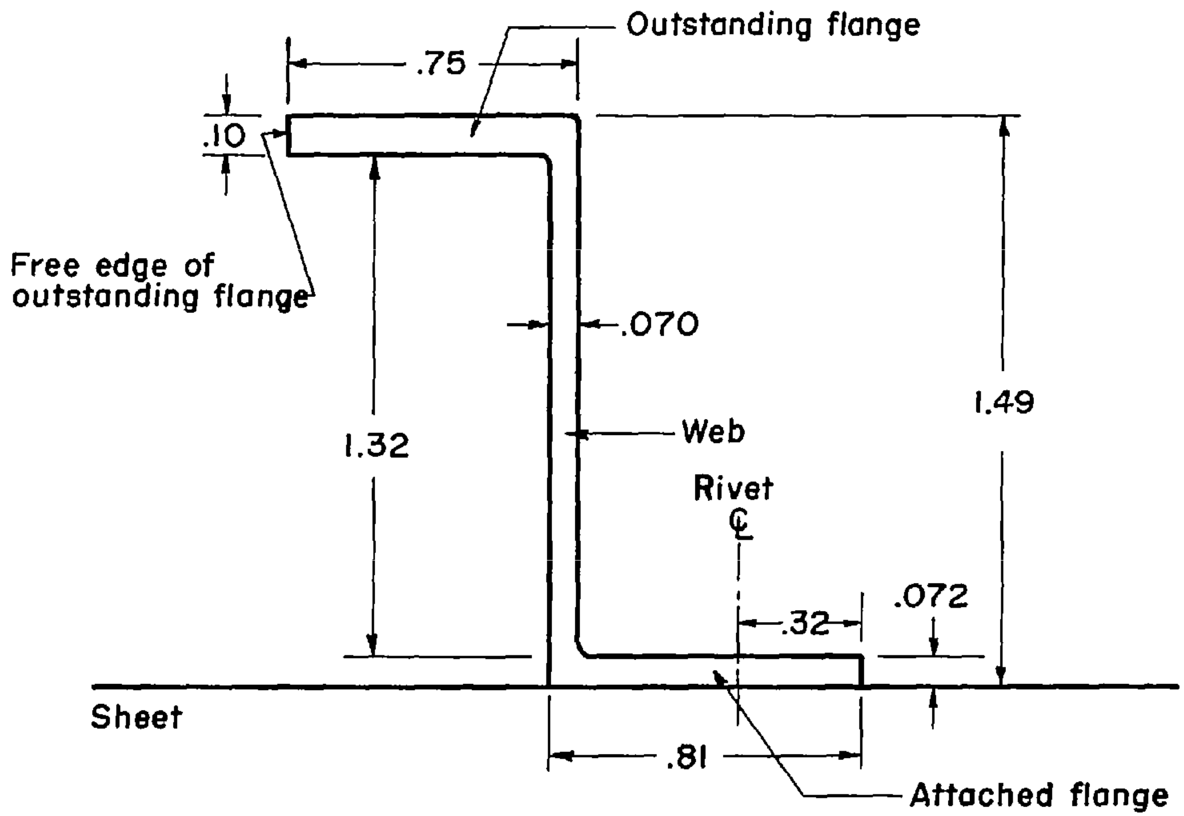


Figure 3.- Average cross-sectional dimensions of stringers of riveted panels Rf-4, Rf-5, Rf-6, Rp-10, Rp-11, Rp-12, Rb-16, Rb-17, and Rb-18. All dimensions are in inches.

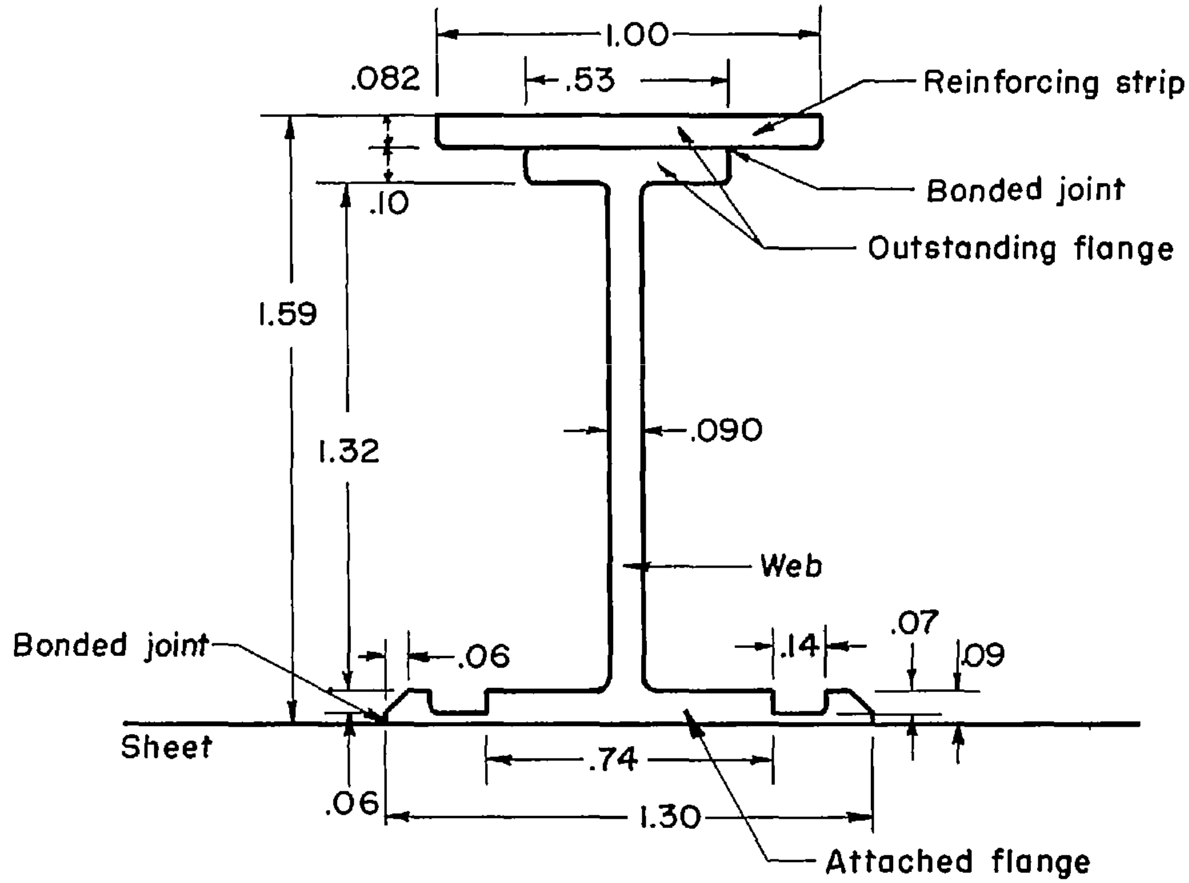


Figure 4.- Average cross-sectional dimensions of stringers of Metlbond bonded panels Mf-19, Mf-20, and Mf-21. All dimensions are in inches.

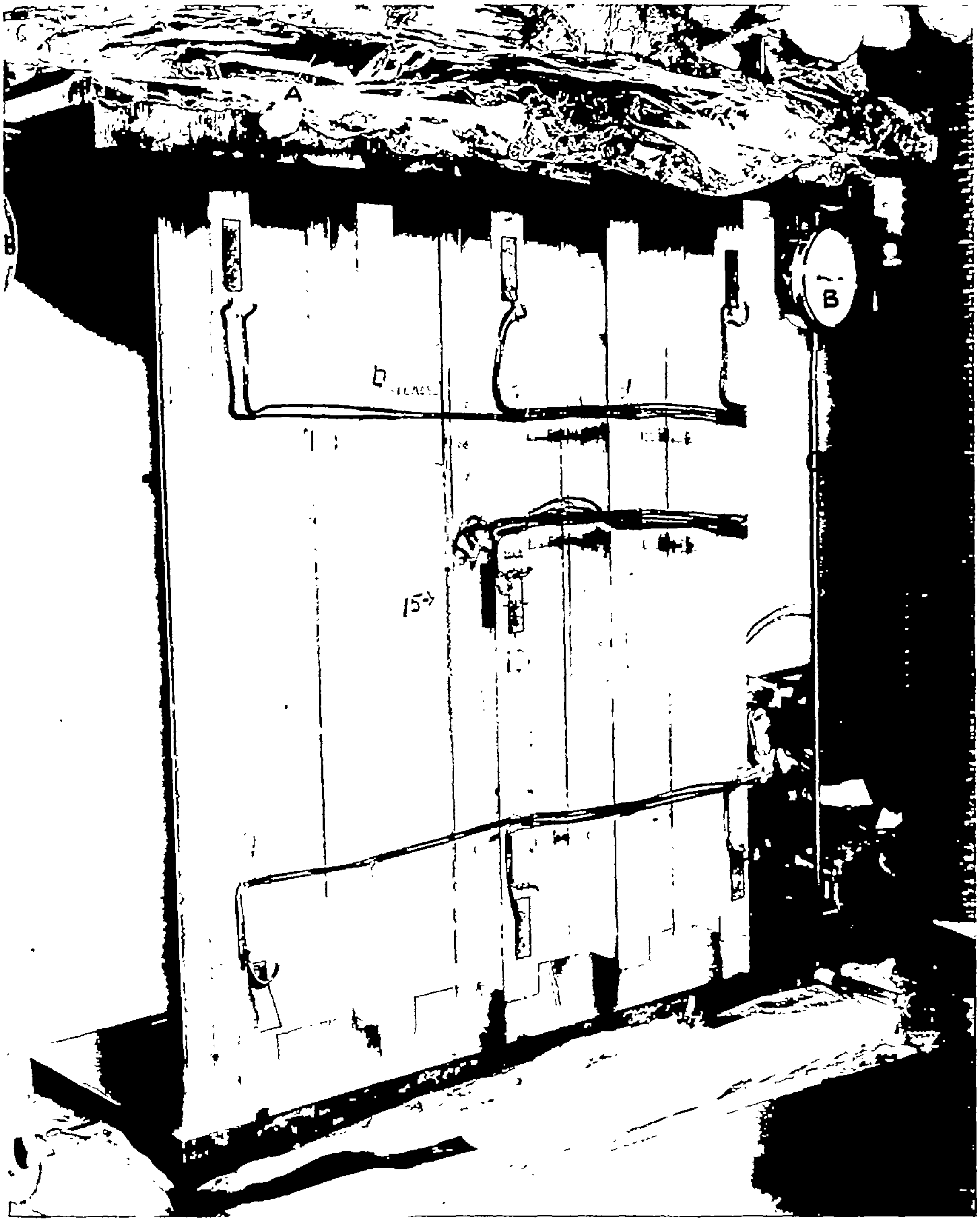


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Figure 5.- Front view of axial flat-end compression test of Araldite bonded panel Af-2 at 3,000-pound load.

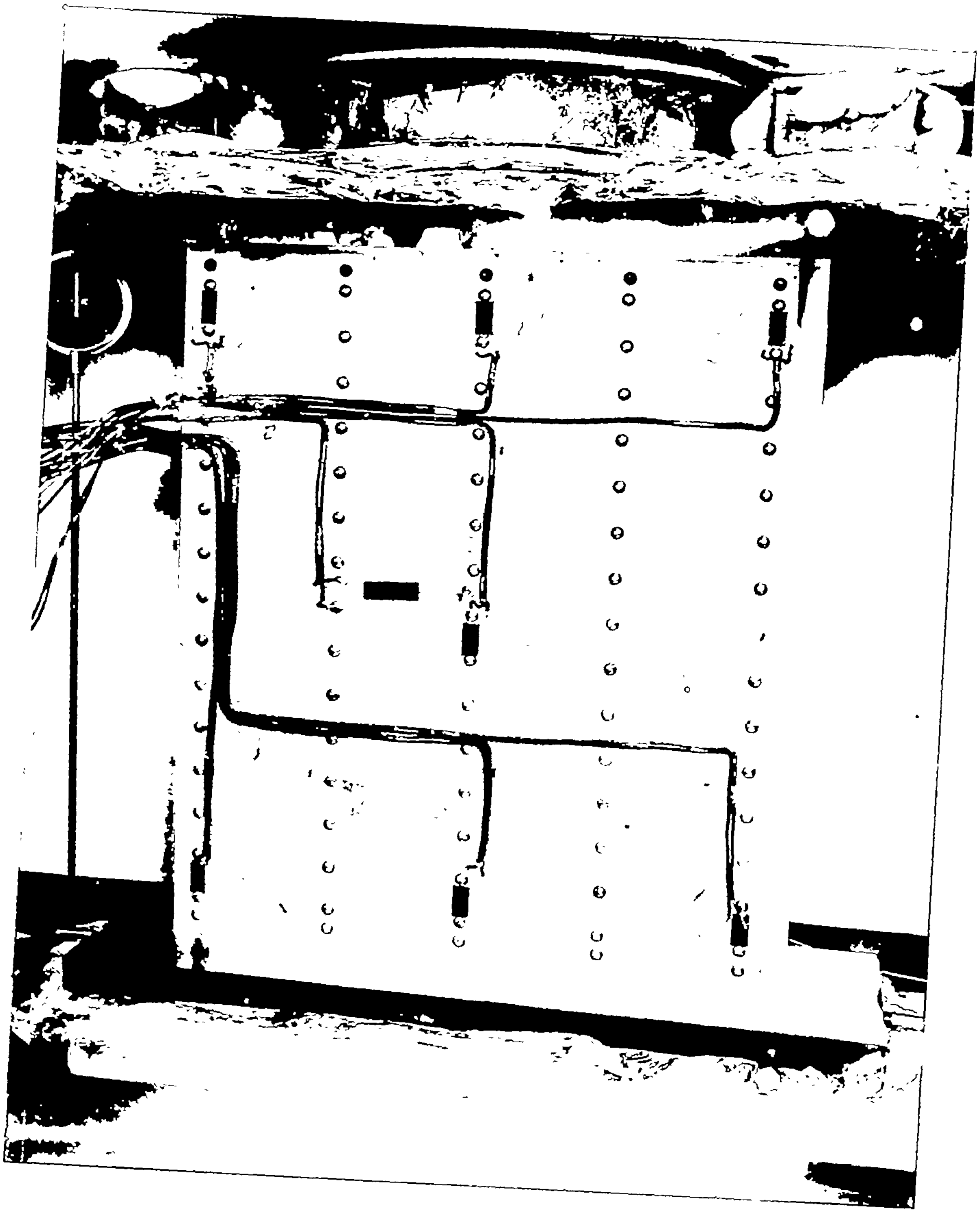

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Figure 6.- Rear view of axial flat-end compression test of riveted panel Rf-6 at 56,000-pound load.

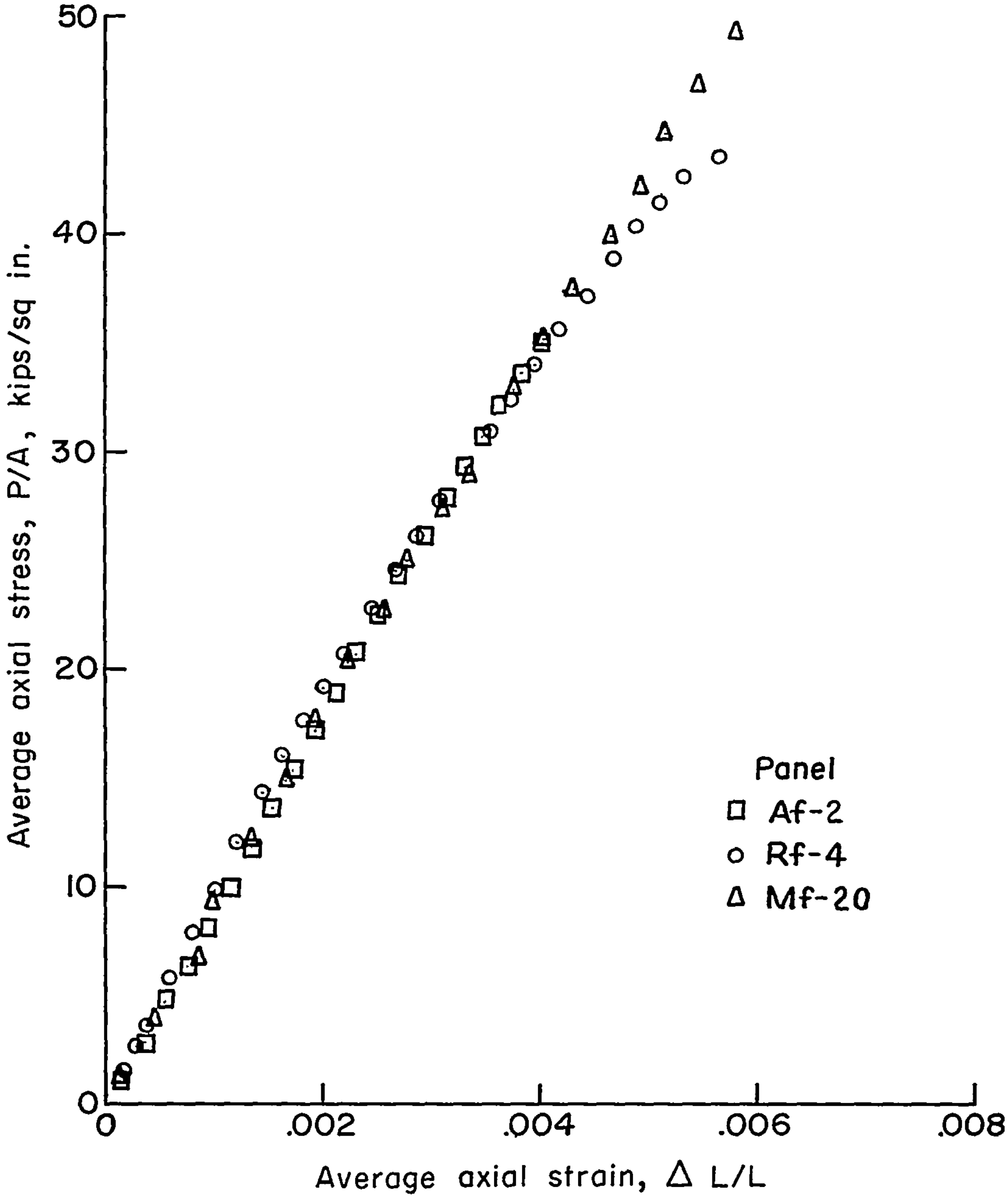

Figure 7.- Average axial stress versus average axial strain for representative panels Af-2, Rf-4, and Mf-20 in axial flat-end compression. L is the length of the panel.

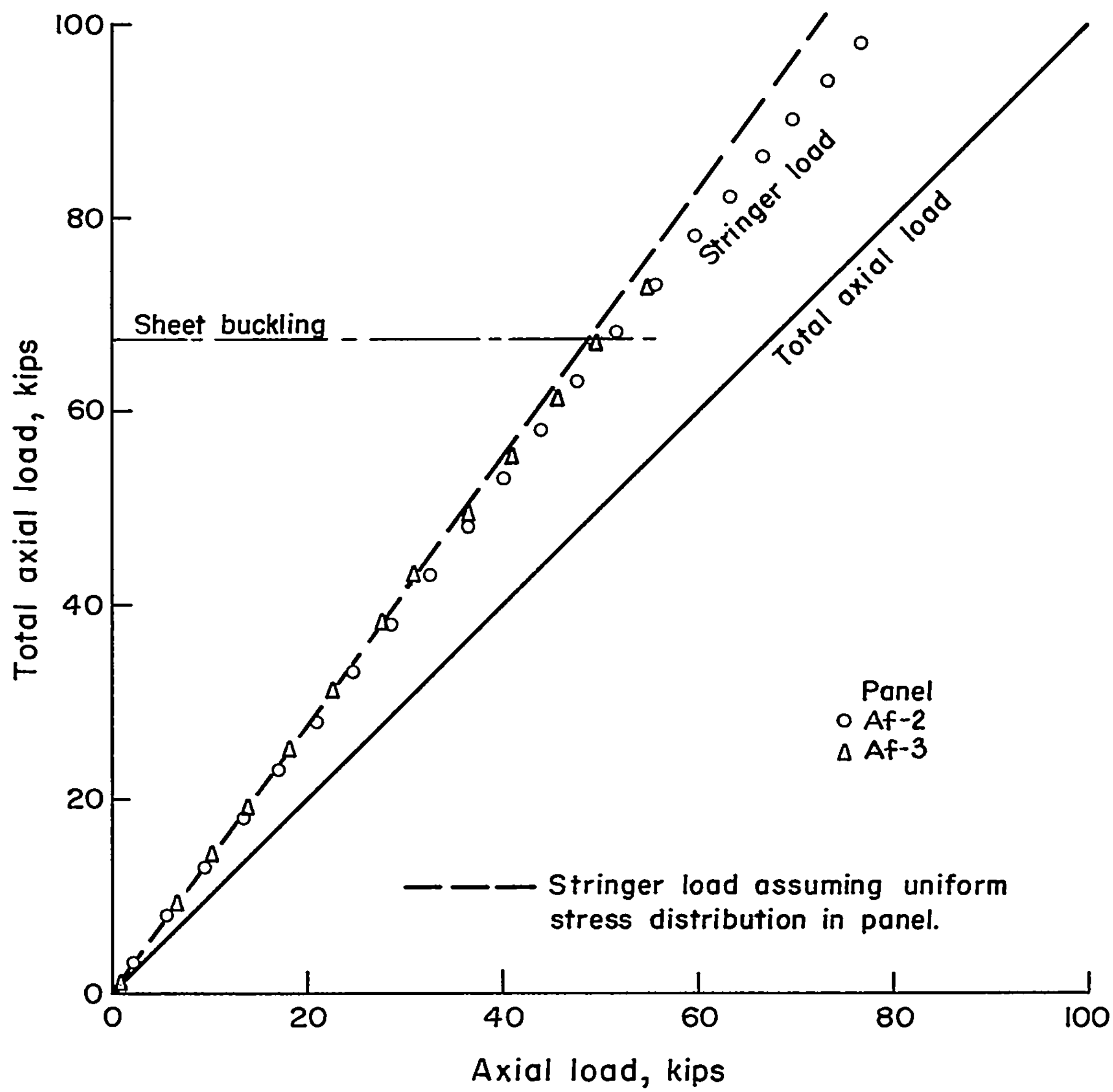

Figure 8.- Stringer load as a function of total load for Araldite bonded panels Af-2 and Af-3 in axial flat-end compression.

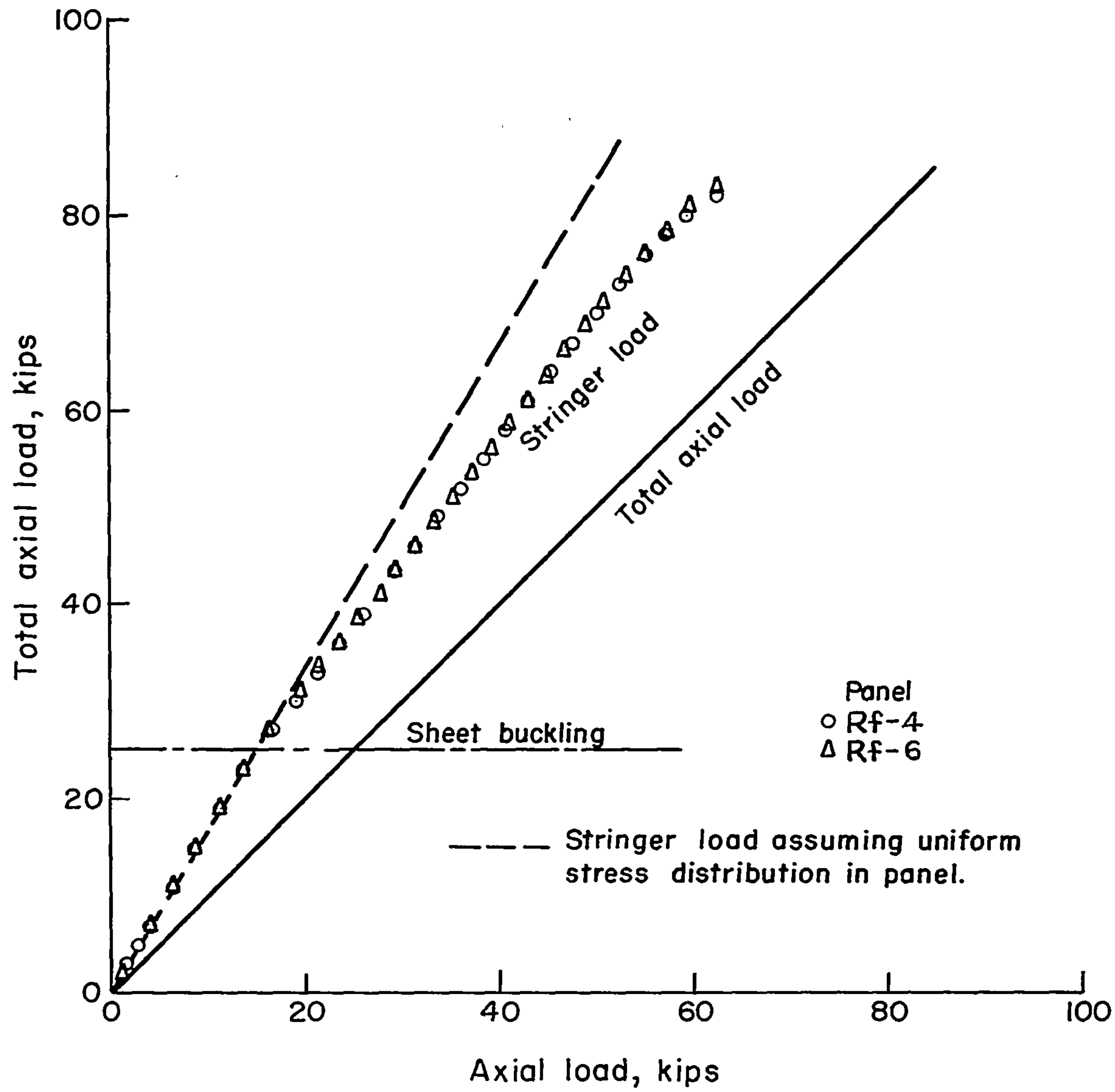

Figure 9.- Stringer load as a function of total load for riveted panels Rf-4 and Rf-6 in axial flat-end compression.

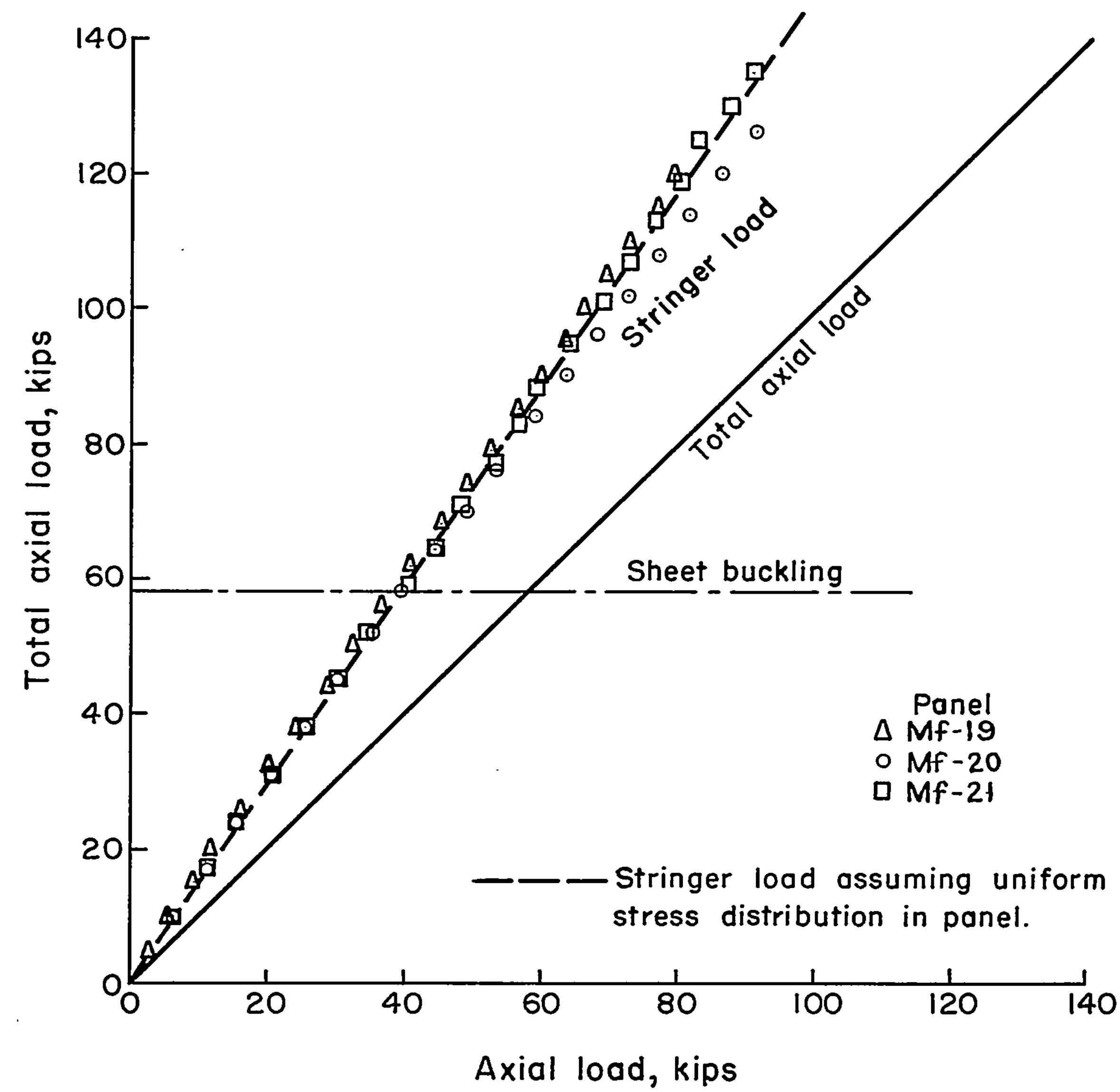

Figure 10.- Stringer load as a function of total load for Metlbond bonded panels Mf-19, Mf-20, and Mf-21 in axial flat-end compression.

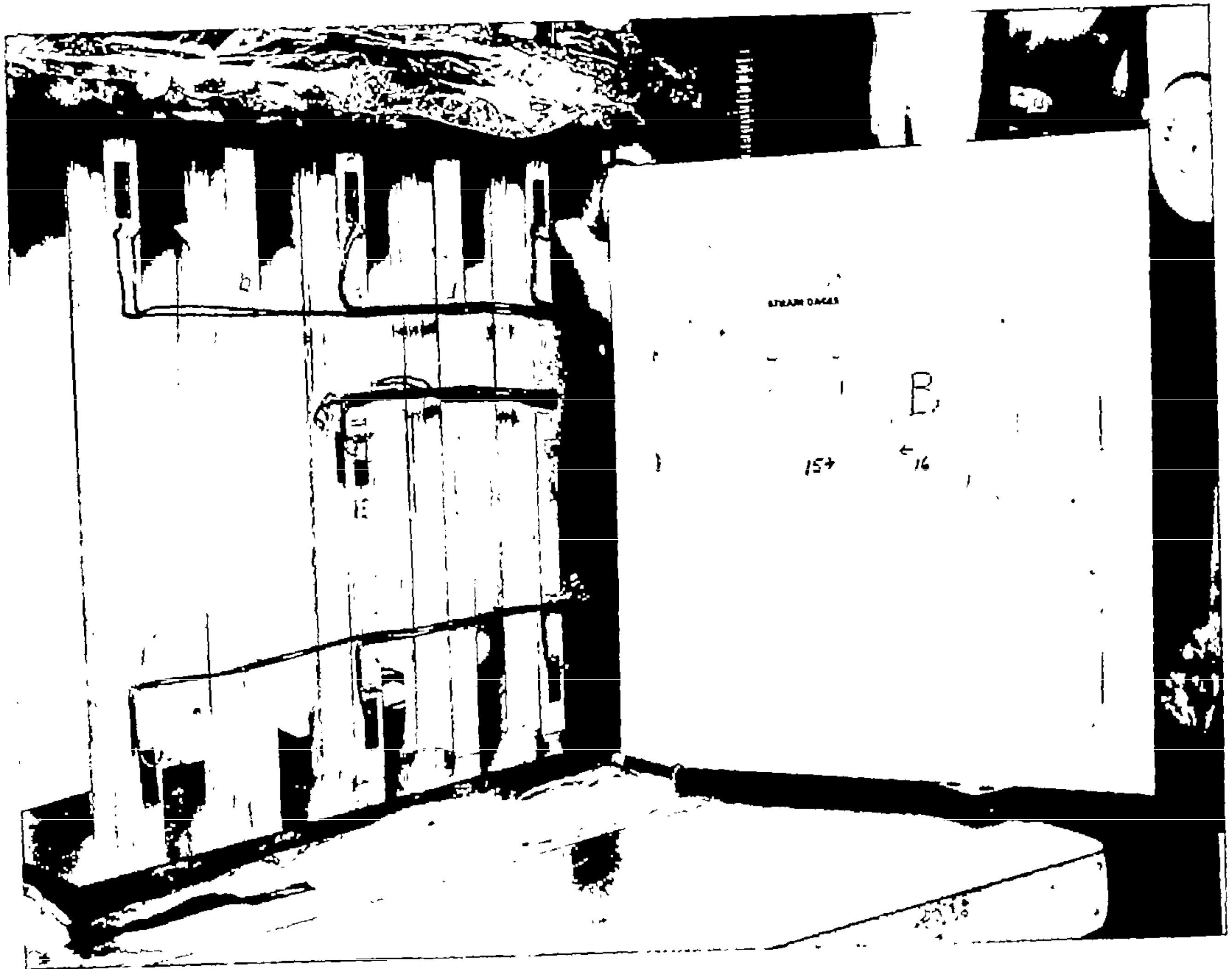

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Figure 11.- Araldite bonded panel Af-2 after sheet ripped free of stringers at 101,800-pound load in axial flat-end compression.

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Figure 12.- Stringers and reinforcing strips of Araldite bonded panel Af-2 after failure in axial flat-end compression.

Figure 13.- Araldite bonded panel Af-3 after initial failure in bond at 78,000-pound load in axial flat-end compression.

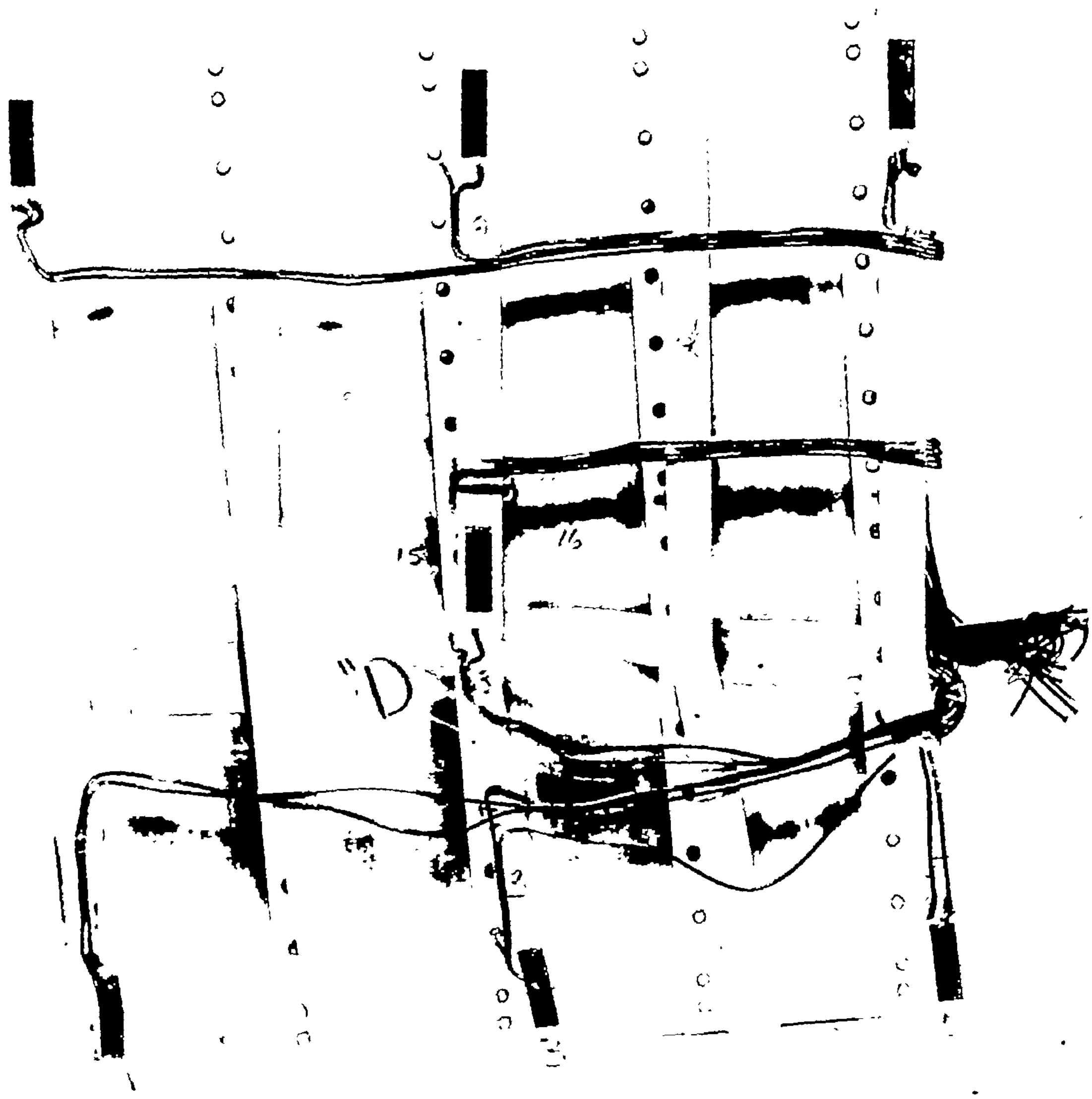

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Figure 14.- Riveted panel Rf-4 after local buckling failure at 82,700-pound load in axial flat-end compression.

L-83300

Figure 15.- Metlbond bonded panel Mf-21 after failure at 142,000-pound load in axial flat-end compression.

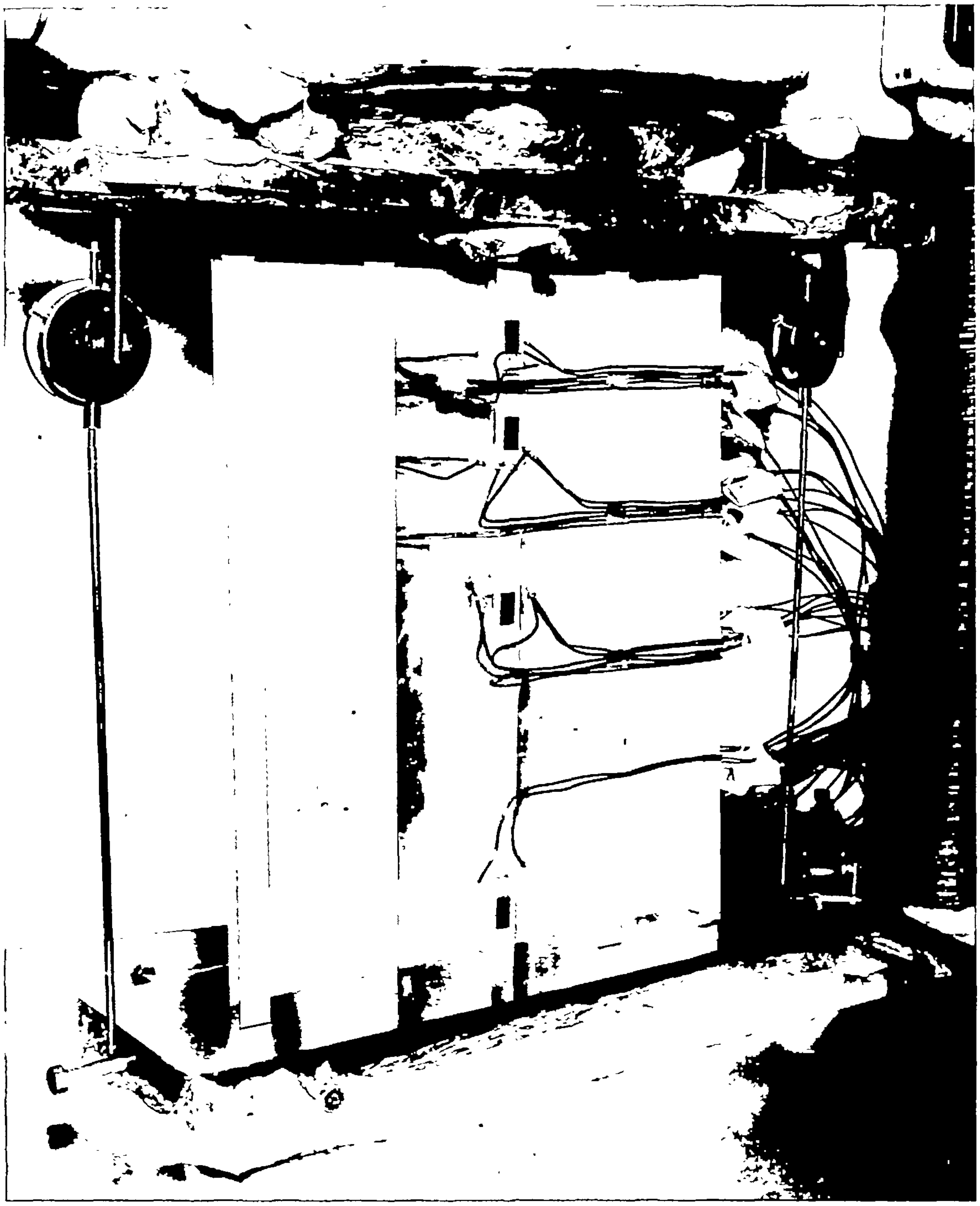

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Figure 16.- Riveted panel Rp-11 at 10,000-pound load in axial center-stringer compression test.

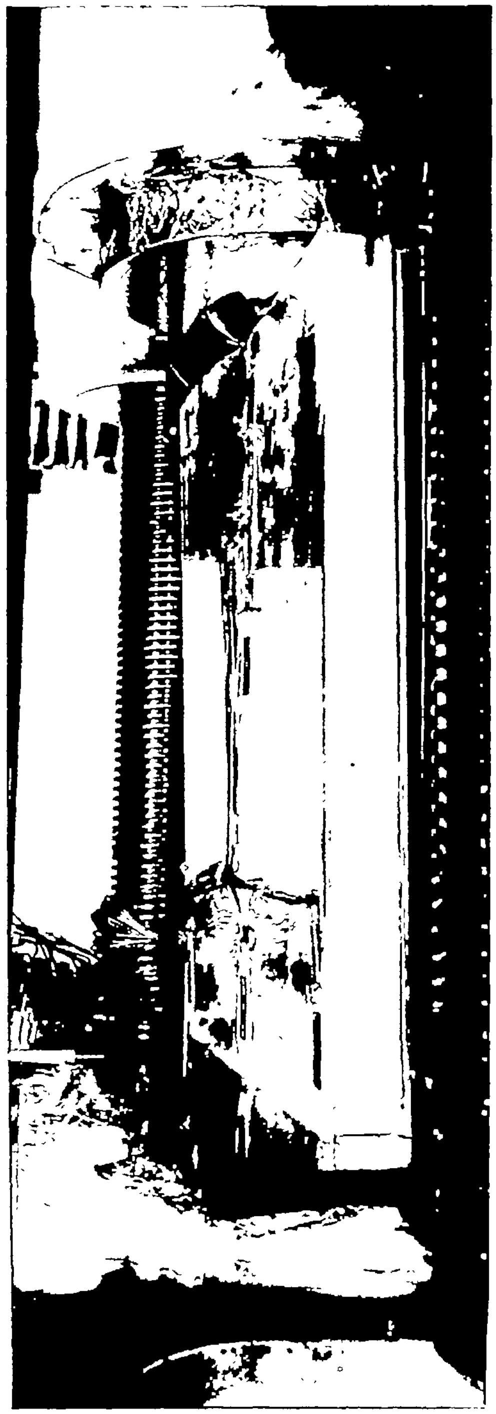

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Figure 17.- Araldite bonded panel Ap-9 at 14,750-pound load in axial center-stringer compression test.

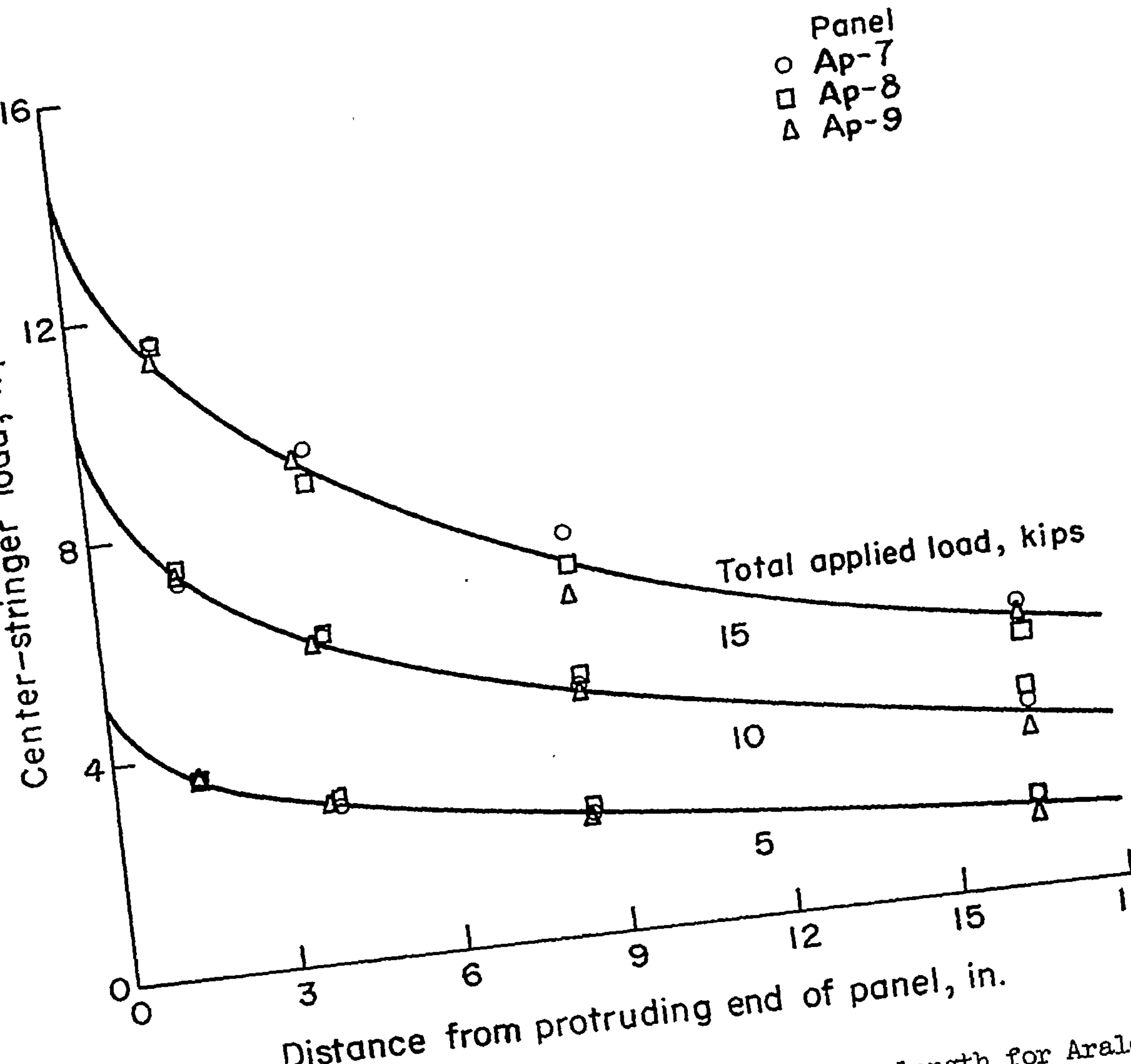

Figure 18.- Center-stringer load as a function of its length for Araldite bonded panels Ap-7, Ap-8, and Ap-9 at approximately one-fourth, one-half, and three-fourths of initial failure load.

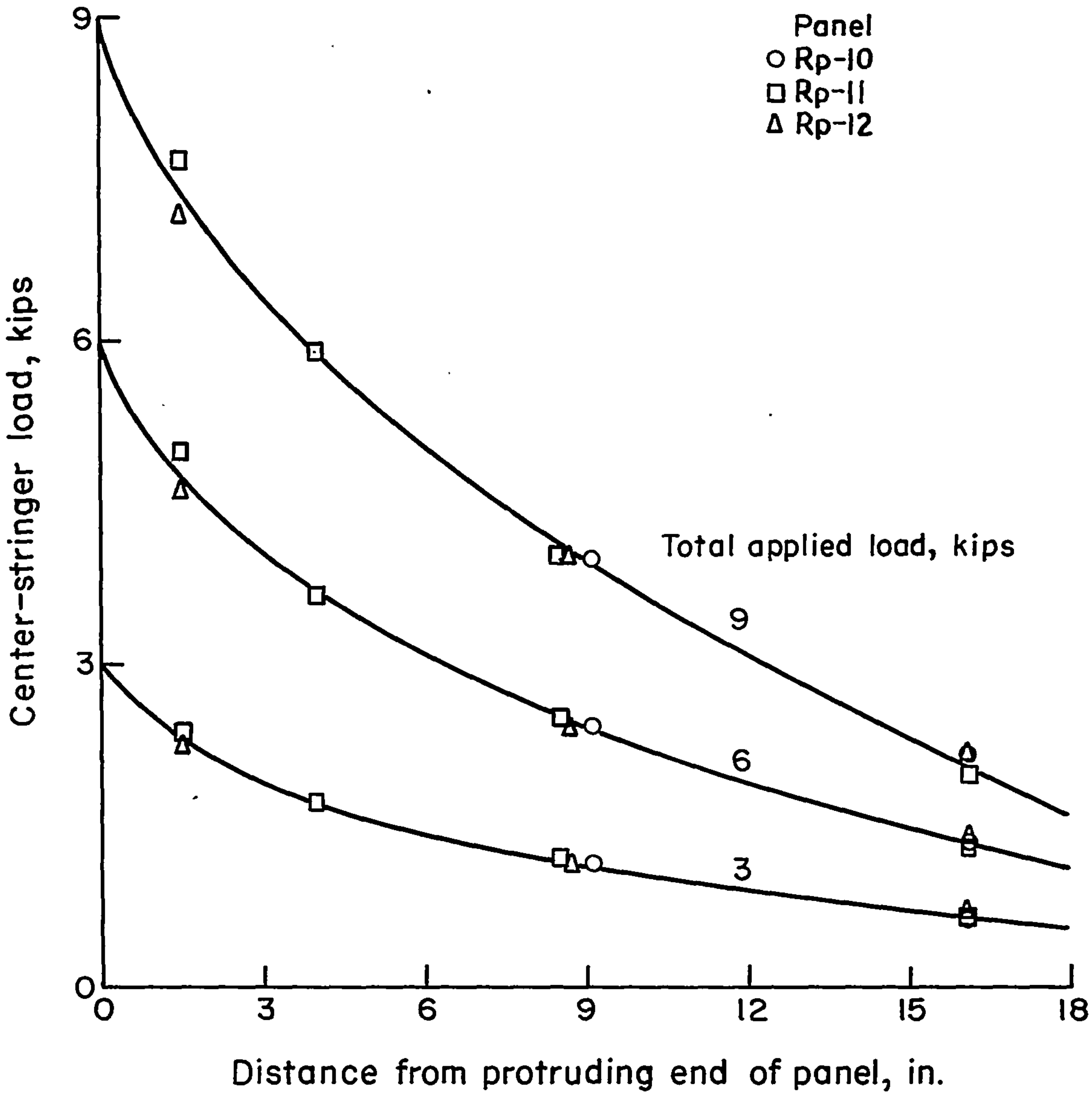

Figure 19.- Center-stringer load as a function of its length for riveted panels Rp-10, Rp-11, and Rp-12 at approximately one-fourth, one-half, and three-fourths of initial failure load.

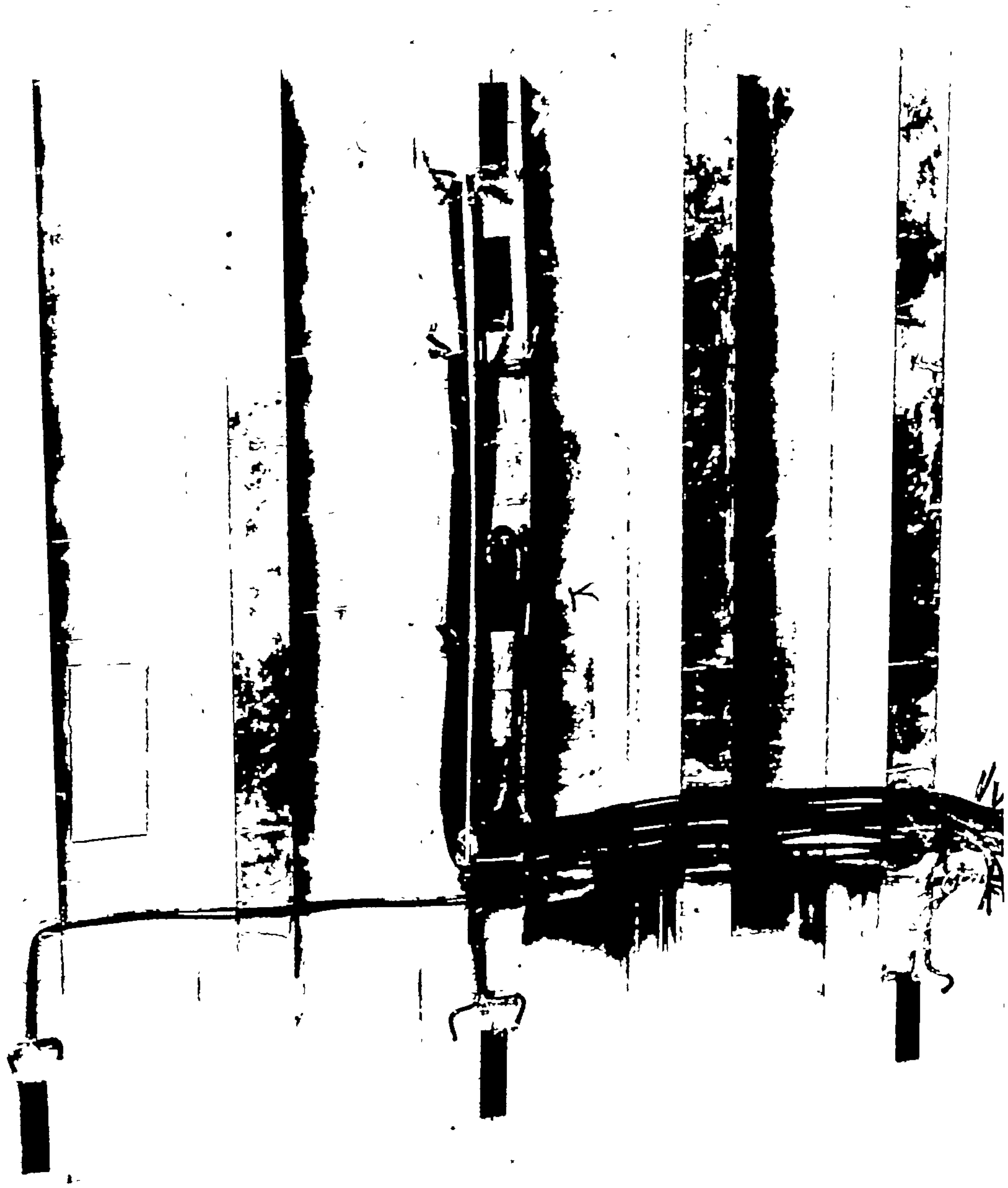

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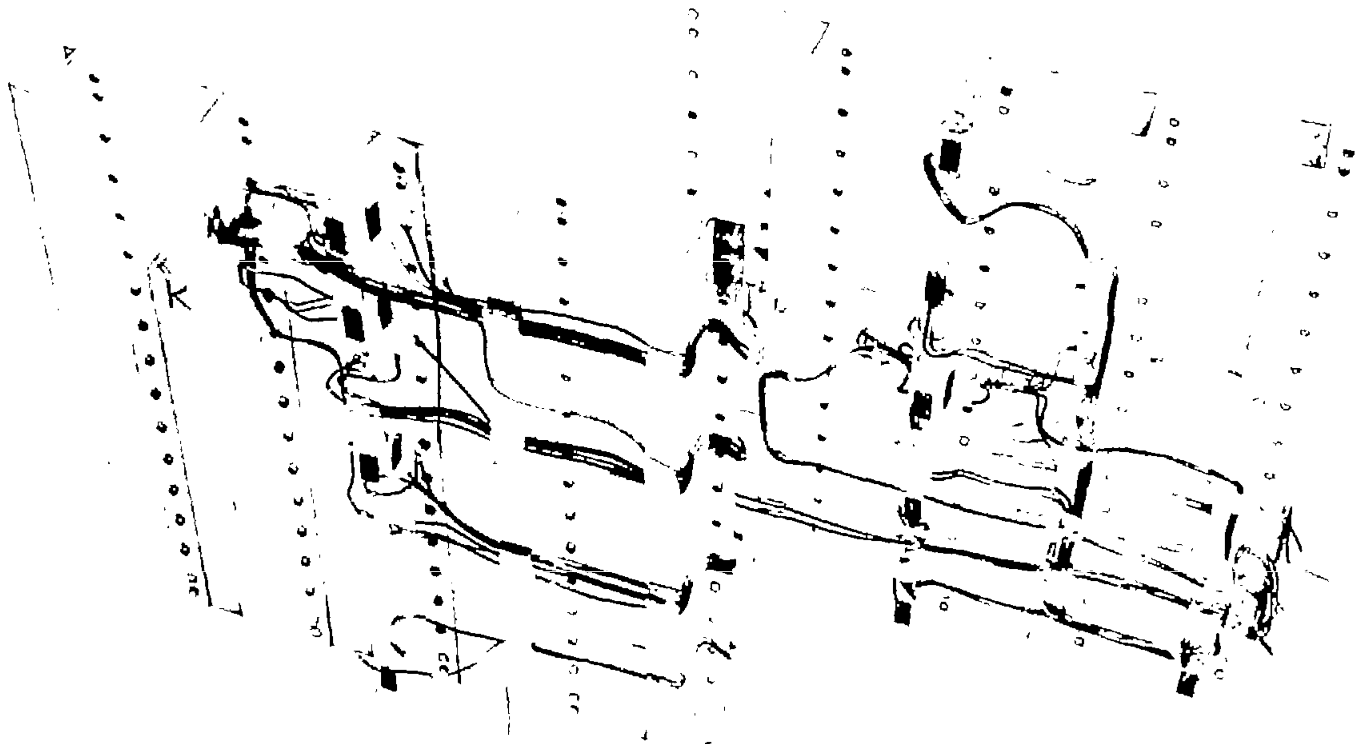
Figure 20.- Araldite bonded panel Ap-7 after column failure of center stringer at 23,500-pound load.



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(a) Riveted panel Rp-11 after torsional buckling failure of center stringer at 13,400-pound load.

(b) Riveted panel Rp-10 after local crushing failure in protrusion of center stringer at 15,700-pound load.

Figure 21.- Riveted protruding-stringer panels after failure.

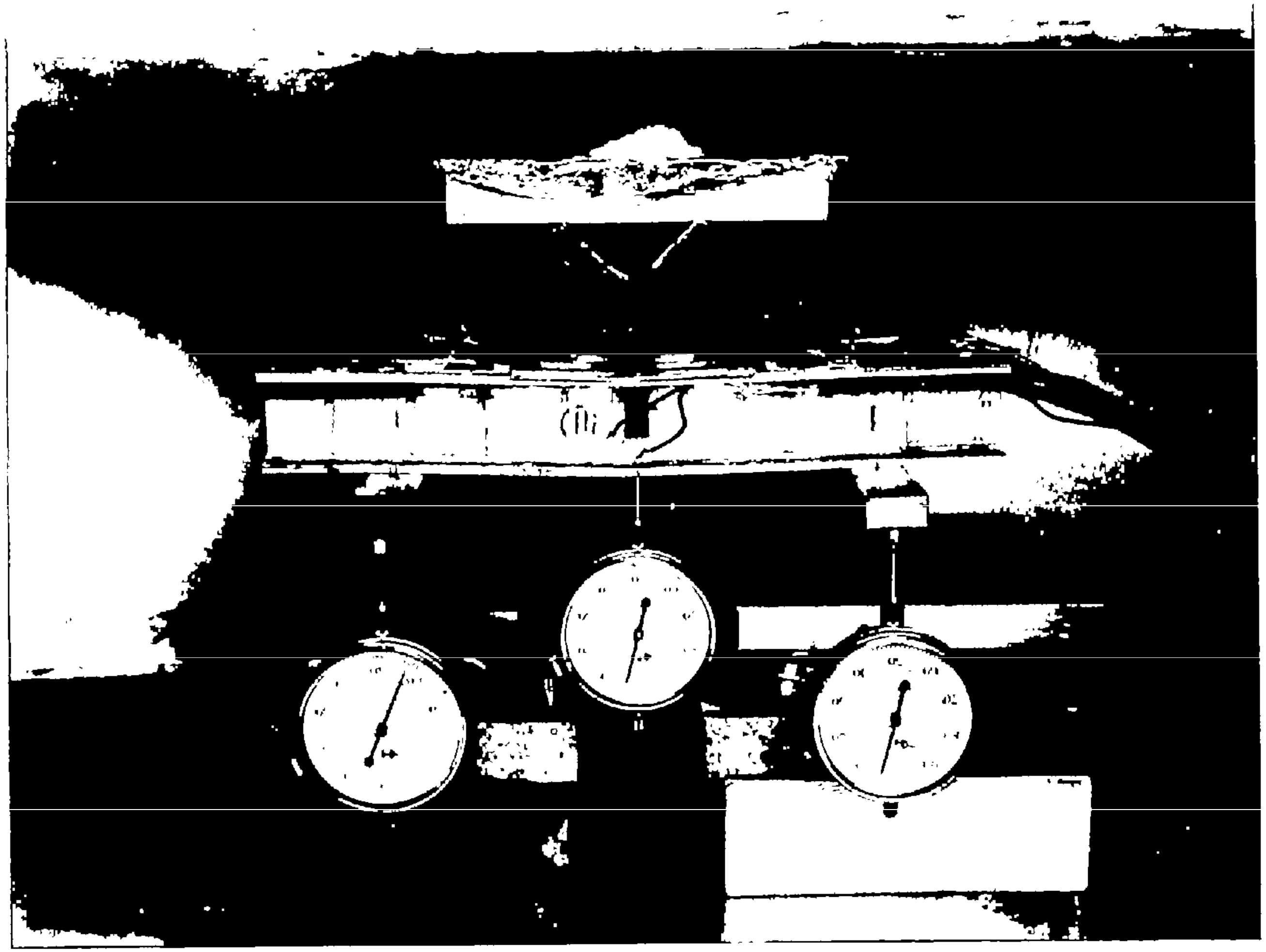

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Figure 22.- Araldite bonded panel Ab-14 at 8,700-pound load in bending test.

L-83306

Figure 23.- Riveted panel Rb-18 at 10,000-pound load in bending test with dial gages removed.

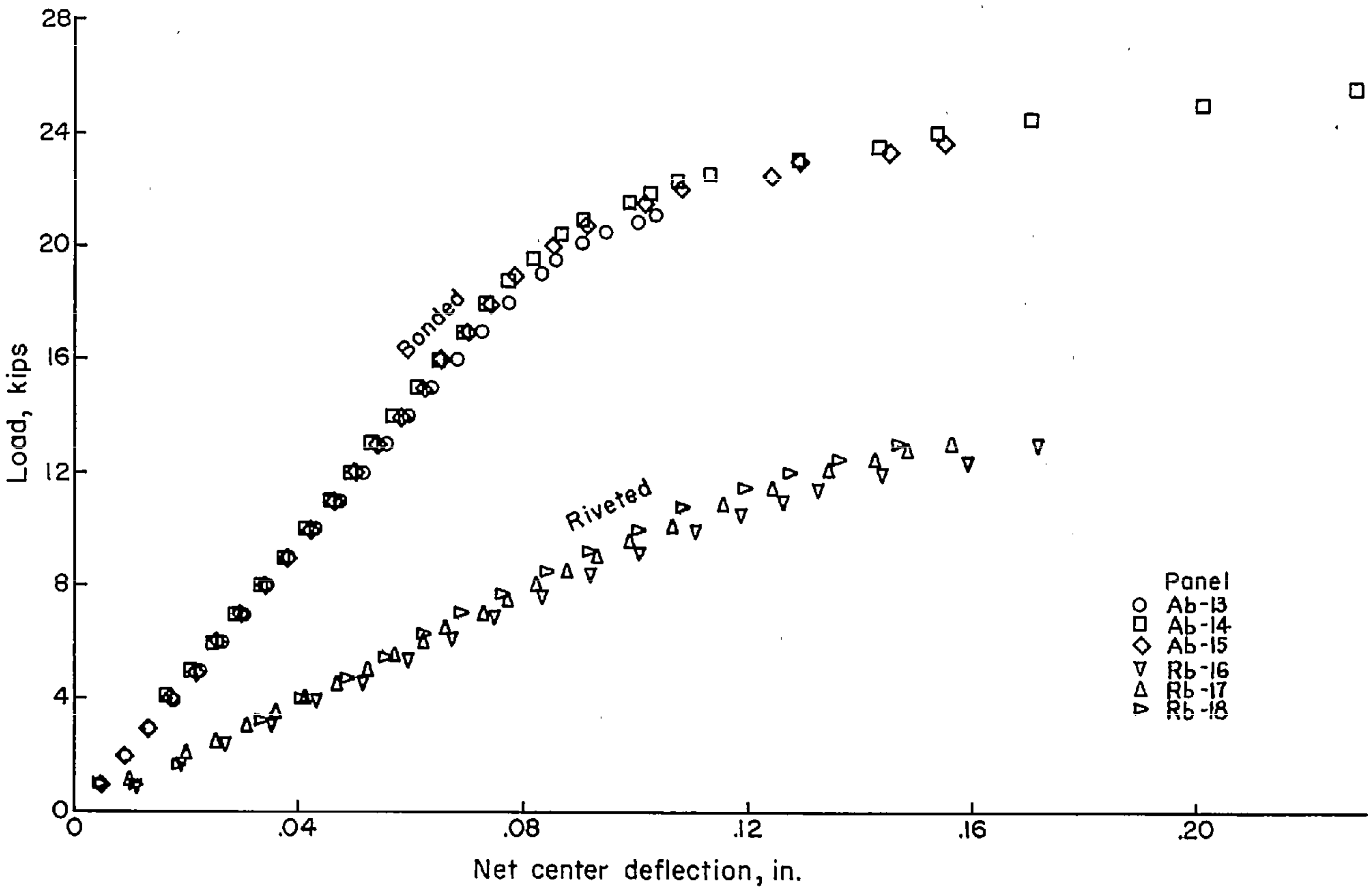

Figure 24.- Load-deflection curves for Araldite bonded panels Ab-13, Ab-14, and Ab-15, and riveted panels Rb-16, Rb-17, and Rb-18 in bending tests.

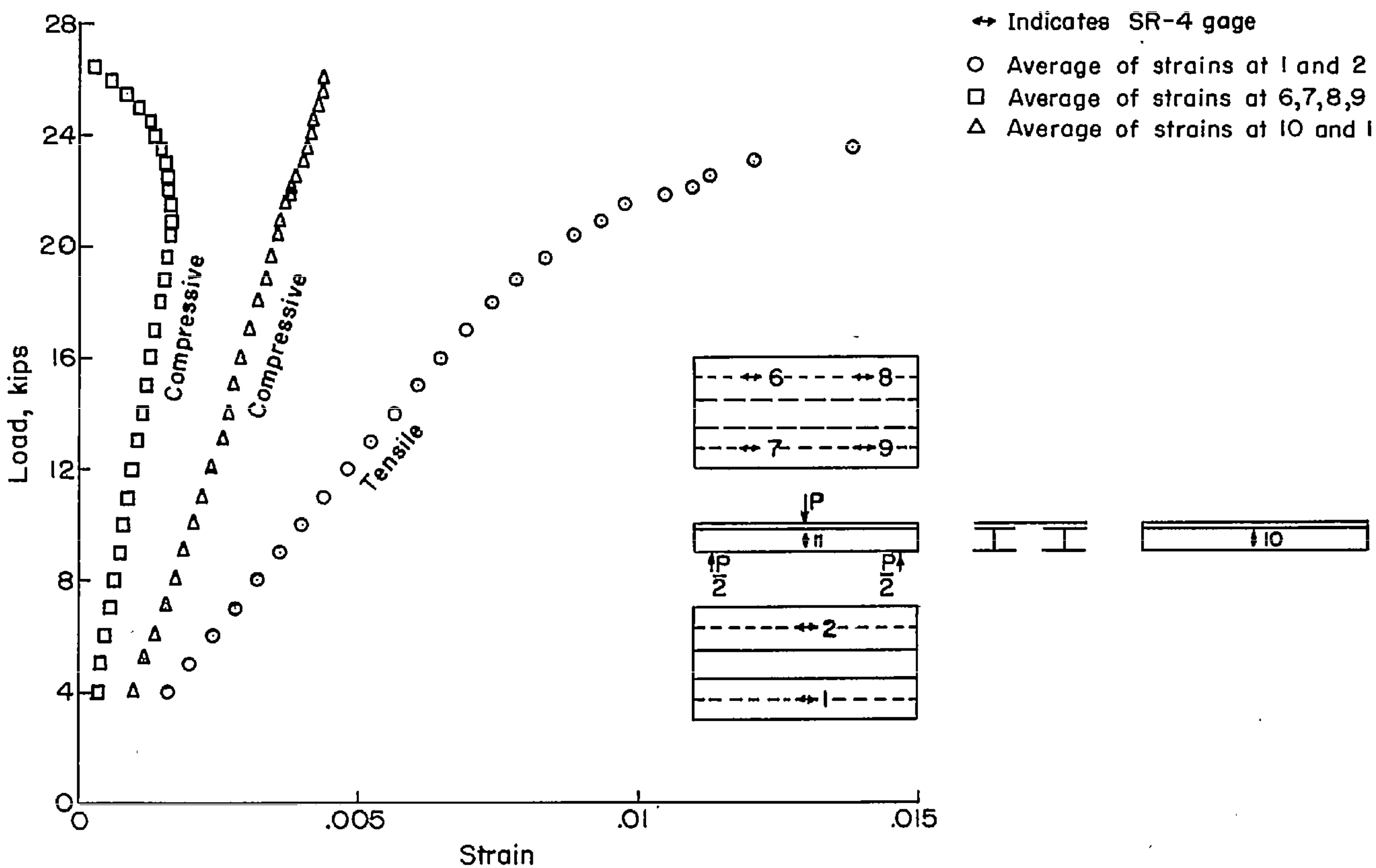

Figure 25.- Load-strain curves for Araldite bonded panel Ab-14 in bending test.

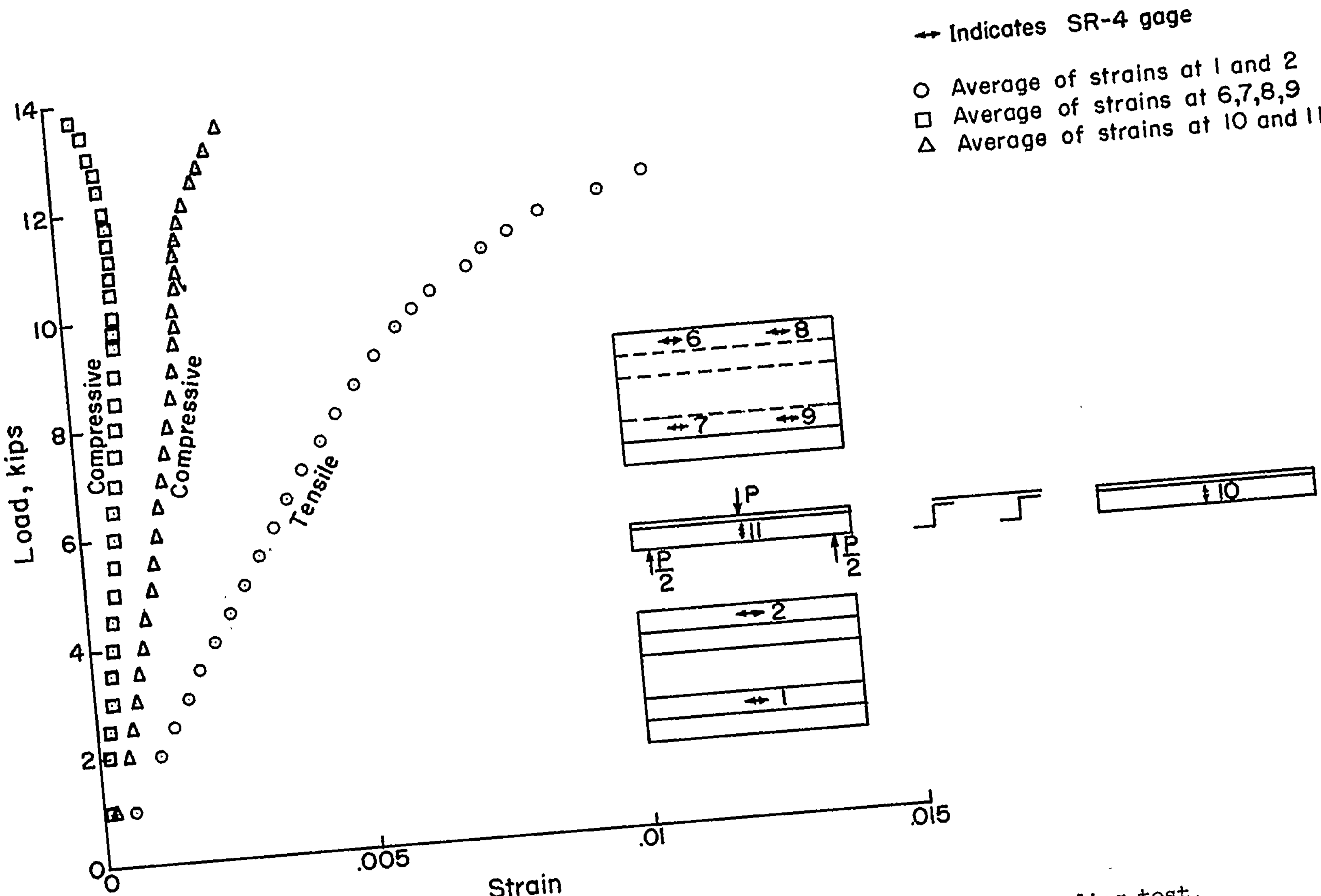

Figure 26.- Load-strain curves for riveted panel Rb-17 in bending test.

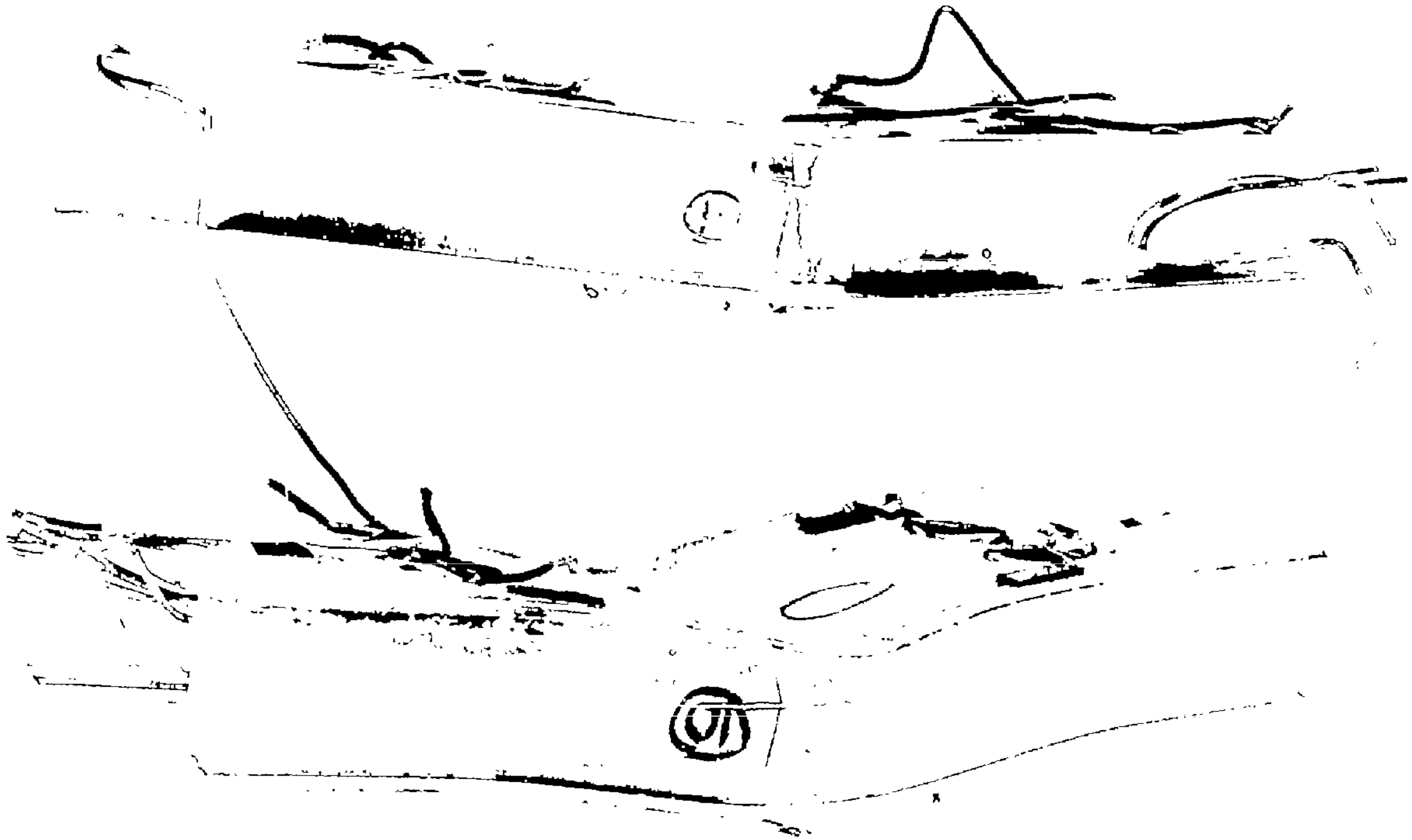

Figure 27.- Riveted panel Rb-18 (top) and Araldite bonded panel Ab-15 after failure at 14,300- and 26,200-pound loads, respectively, in bending tests.

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